Modular Modeling System (MMS): A Code for the Dynamic Simulation of Fossil and Nuclear Power Plants
Overview and General Theory

EPRI

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Modular Modeling System (MMS): A Code for the Dynamic Simulation of Fossil and Nuclear Power Plants
Overview and General Theory

Prepared by

THE BABCOCK & WILCOX COMPANY
Lynchburg Research Center
Lynchburg, Virginia 24505

BECHTEL GROUP, INC.
50 Beale Street
San Francisco, California 94119

Principal Investigators
L. P. Smith
R. R. Dixon

Principal Investigator
S. W. W. Shor

Prepared for

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NOTICE

ABSTRACT

The Modular Modeling System (MMS) is a computer code developed by EPRI to facili-
tate modeling the dynamics of fossil-fueled and nuclear steam electric power
plants. It is intended to assist in the power plant design process and during
later operation for troubleshooting, setting control system gains, validation of
simulators, checking operating procedures, and forecasting the consequences of
severe transient tests before they are actually run. The code is able at present
to model fossil-fueled plants of almost all conventional configurations, pres-
surized water reactor (PWR) coolant systems, and the balance of plant of both boil-
ing water reactor (BWR) and PWR plants. Enhancements scheduled for release in
early 1984 will permit the MMS to model BWR nuclear steam supply system components
in normal operation and PWR reactor coolant systems which have been breached and
are experiencing two-phase flow. The MMS provides preprogrammed modules that rep-
resent power plant components. These are automatically interconnected in the
arrangement determined by the user by a high level simulation language which is an
integral part of the MMS. The language also provides a run time executive, the
integration algorithm, linear analysis routines, and many user convenience fea-
tures.

This report provides the theoretical basis of the MMS, a description of each
module, and an executive summary that describes the present status of the code and
its major features, together with the validation and testing that it has undergone.
Full documentation of the MMS is found in the Computer Code Manual, which is
available to users under license to EPRI.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

The development of the Modular Modeling System (MMS) computer code has been
supported jointly by the Coal Combustion Systems Division (under RP1184) and the
Nuclear Power Division (under RP1163) since its inception in 1979. The primary
function of the MMS code is to provide computer simulation of the dynamic
performance of fossil and nuclear plants.

The MMS code, intended for use in plant design and operation, consists of a library
of plant component modules that can be assembled by the user in order to represent
all plant configurations of practical interest. The MMS model can then be used to
analyze the desired and necessary plant transients for diagnosis of faults or
prediction of response.

PROJECT OBJECTIVE

The objective of this project (RP1163-1 and RP1184-2) is to develop an easy-to-use,
flexible, economical, and accurate systems analysis code that can be used for
simulating and analyzing the dynamic performance of nuclear and fossil power plants,
their subsystems' controls, and components.

The emphasis on the concept of "modularity" allows users to select the appropriate
module from the main library. Each of the modules has been and will be verified and
qualified by a number of users in relevant applications. The potential applications
of the code are (1) analyses, procedures evaluation, and simulator model qualifi-
cations of LWR transients and accidents; (2) fossil plant dynamic analysis to
improve plant availability and heat rate (particularly for cycling units); and
(3) optimal power plant control system design and analysis.

PROJECT RESULTS

The current MMS-01 library consists of 40 modules representing components used in
conventional fossil and nuclear power plants. Modules include balance of plant

(pipes, valves, pumps, feedwater heaters, steam turbines, flash tanks, and condenser), control elements and systems, fossil boilers (furnaces, superheaters, and attemperators), and LWR systems (PWR reactors, pressurizer, moisture separators, and once-through and U-tube steam generators). All modules are completely self-contained and may be interconnected in many possible arrangements in order to represent desired power plant system configurations.

The MMS code has been written in two high-level dynamic simulation languages: ACSL and EASY-5. The ACSL language was developed and is supported by Mitchell and Gauthier, and EASY-5 was written by Boeing Computer Services Company. Commercial simulation languages were intentionally chosen (1) to provide better and continued support to the code users, (2) to provide a well-tested library of analysis packages, and (3) to eliminate new numerical solution development.

A prerelease user's group, comprising nine EPRI member utilities, has participated in the validation of MMS-01 for a period of 10 months. This effort has resulted in the enhancement of the code as well as improvements in the user documentation.

The documentation for the MMS code development is presented in four volumes (EPRI Computer Code Manual CS/NP-3016-CCM):

- Volume 1: Theory Manual. This volume discusses the theoretical and phenomenological basis for the equations.

- Volume 2: Programmers Manual. This volume presents the general coding philosophy, utilization of the simulation languages in module construction, listing of the modules, steam properties, and information on auxiliary programs that can be used.

- Volume 3: User's Manual. This volume gives the input data requirements for each module and describes examples of model construction with the modules.

- Volume 4: Applications Report. This volume describes the extensive verification effort associated with the code development phase of the project and presents results of analysis used to evaluate and qualify the code for various applications.

The MMS code will be continuously refined and expanded to fully serve the needs of the utilities in the years ahead. The code will become available commercially as

well as being released through the Electric Power Software Center. The MMS code should be applicable to utilities for use in plant design, operation, and safety analysis.

A. F. Armor, Project Manager
F. K. L. Wong, Project Manager
Coal Combustion Systems

S. M. Divakaruni, Project Manager
J. P. Sursock, Project Manager
Nuclear Power Division

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EXECUTIVE SUMMARY

This report describes the theory, organization, and significant features of the
Modular Modeling System (MMS), a computer code developed by the Electric Power
Research Institute (EPRI) to facilitate the modeling of the dynamics of both
fossil-fueled and nuclear steam electric power plants. Details of the formulation
of specific modules and instructions on use of the code are found in the MMS Compu-
ter Code Manual of which this report is a small part. Validation of the MMS
against transients recorded in two nuclear power plants and one fossil-fired power
plant is reported by EPRI-CS/NP-2945, "Modular Modeling System Validation: Tran-
sients in Fossil and Nuclear Power Plants."

PURPOSE OF MMS

The MMS is intended to permit the modeling of the dynamic performance of power
plants, quickly and inexpensively enough to insert modeling into the iterative pro-
cesses of design and plant troubleshooting. It achieves this capability by using
preprogrammed modules representing power plant components. The user inserts param-
eters into the modules to make them represent the components of a particular plant.
He can then cause the code to interconnect the modules in any order which is feasi-
ble in an actual power plant. A side benefit of this modular approach is a
reduction in the level of modeling skill required. Engineers whose primary exper-
tise is in fields other than modeling can rapidly become effective modelers without
having to become proficient in the difficult programming of the component models
themselves. Users also need not become involved in the details of interconnecting
models of different components because this is handled automatically by the code.
This simplicity of use contributes significantly to cutting the cost of modeling,
most of which lies in the engineering work and not in the computer services.

The MMS is intended for use during both plant design and plant operation. The MMS
code permits simulation of a wide range of transients which may occur with a pro-
posed plant configuration (for example, the consequences of a heater drain pump
trip). It permits investigation of the possible causes and consequences of an
actual transient had it been permitted to continue without interruption to com-
pletion. The MMS code can be used to test proposed plant operating procedures and

to determine the probable impact on transient behavior of time lags and errors in instruments used by plant operators while following the procedures. It permits testing of alternative control system configurations during the design stage, leading to an optimized design. It can be used to determine settings of control gains during the preoperational checkout of a plant, eliminating the need for extensive transient operation to arrive through trial and error at a satisfactory adjustment of the controls. It can be used for nuclear plant accident and operational transient analysis. And it is being employed to verify the ability of nuclear plant training simulators to reproduce transients which have never occurred in practice so that operators may train in the prevention of accidents.

HISTORY OF DEVELOPMENT

Development of the MMS was begun in August, 1978. The first level code, MMS-01, was subjected to a year's test by a prerelease users group consisting of utility members of EPRI. It was then released in April, 1983, for general use under EPRI license. With its present library of 40 modules, MMS-01 can model fossil-fueled power plants of all conventional configurations, pressurized water reactor (PWR) plant coolant systems, and the balance of plant of both boiling water reactor (BWR) and PWR plants. The second level, MMS-02, is now being tested and is scheduled for release in early 1984. It will add the capability to model BWR nuclear steam supply system components in normal operation and PWR reactor coolant systems under faulted conditions which result in two-phase flow.

KEY FEATURES OF MMS

Simulation Language

The MMS in its present easy-to-use form would not have been possible without the use of a simulation language. The simulation language not only automatically interconnects the preprogrammed modules in the order determined by the user, but also sorts their equations into an executable sequence. It translates the short source program written on simulation language (largely prepared by filling in blanks on user work sheets) into a FORTRAN program many times as long. It then causes the FORTRAN program to be compiled. The simulation language also provides the integration routine, a run time executive, and many convenience features. These include linear analysis, output, table input, interpolation, and other routines.

The MMS is available in two versions using two different simulation languages: the Advanced Continuous Simulation Language (ACSL) sponsored by Mitchell & Gauthier Associates; and EASY5, sponsored by the Boeing Computer Services Company. Although alike in many respects, each simulation language has some advantages not shared by the other. Principal differences are in nomenclature, linear analysis routines, and input/output format. MMS-01 was first developed using the ACSL language. This was the version tested by the Prerelease Users Group. The ACSL-based version of MMS-01 has since been translated from ACSL into EASY5 by an automatic translator. The EASY5 version is scheduled for testing during 1983.

Formulation of Modules

The modules in the MMS code are developed from first principles as lumped parameter models of components which are recognizable as equivalent to components used in a power plant; for example, feedwater heaters, high pressure turbines, and condensers. A single module representing a superheater stage is provided: this module can be employed several times with different parameter inputs to represent the multiple superheating and reheating stages in a fossil boiler model. The lumped parameter approach permits a single component to be represented by different modules of different levels of complexity to meet different modeling needs. This is desirable because to minimize both engineering and computing costs, the least complex module that will provide sufficient accuracy to achieve a model's objectives should be employed. A PWR nuclear reactor, for example, is represented in MMS-02 by modules of four different levels of complexity. The simplest of these is for use in modeling cases where there is no voiding in the reactor coolant system and all conditions in the reactor are axisymmetric. The most complex of the four can handle two-phase and reverse flow under accident conditions with asymmetry in both coolant flow and neutron flux.

The modules representing fluid components in MMS-01, with a few exceptions such as steam generators, are intended to model fluids only in a single phase (for example, water or steam at any point, with a level separating them) or wet steam moving as a homogeneous fluid. Those modules are also, in general, limited to representing flow in a single direction. The PWR reactor coolant system modules to be included in MMS-02 for PWR accident analysis, on the other hand, can handle flow in either direction and use a drift flux approach to represent the two-phase flow found in a breached reactor coolant system. Both types of modules employ conservation of mass and conservation of energy in their mathematical formulations, but in most cases employ a quasi-steady state rather than a dynamic momentum solution.

Integration and Linear Analysis

The simulation is performed by integrating state variables (for example, enthalpy, pressure) with respect to time. Both simulation languages employed in MMS provide a number of alternative integration algorithms, but MMS normally employs only one of them: Gear's stiff algorithm. (The algorithm details differ slightly between the two simulation languages.) Gear's stiff algorithm is an implicit algorithm. That is, it uses as arguments the values of the state variables at the end of the integration step rather than at the beginning, iterating a single time step until the difference between the results of successive calculations falls below an acceptable limit. This type of algorithm, unlike the explicit algorithms employed in many other simulations, provides stability in the integration while making time steps that are short compared with the time constants of transients of interest but many orders of magnitude longer than the shortest time constants produced by the model equations. Gear's stiff algorithm employs steps of variable length, automatically increasing their size (often to many seconds) as the rate of a transient decreases toward steady state.

A simulation language also provides linear analysis capability. It first linearizes the model at an operating point selected by the user. It then employs the linearized model for a number of purposes. For example, an equilibrium finder included in the analysis package uses the linear model to find values of state variables that will place the model at steady state prior to starting a transient. The linear analysis routines also calculate eigenvectors and eigenvalues from which improved control system gain settings may be deduced at far lower cost than by cut and try adjustment of gains in successive transient simulations.

VALIDATION OF ACCURACY AND USABILITY

MMS-01 was extensively validated for both accuracy and usability prior to code release.

Accuracy

It was validated for accuracy by reproducing transients recorded in both fossil-fueled and nuclear plants. Because very little transient data recorded in fossil-fueled plants could be found in either published or unpublished form, the MMS project recorded transient data from tests conducted for it on Boston Edison Company's Mystic Unit 7, a 550 MW oil-fired plant. The initial balance of plant modules developed by the MMS project were validated against the recorded plant data before the remainder of the development went forward. That validation is reported

in EPRI CS/NP-2086, "Power Plant Performance Modeling: Dynamic Model Evaluation" dated October 1981. The Mystic 7 data were used again to validate a model which also contained the boiler. That validation is reported in EPRI-CS/NP-2945, "Modular Modeling System Validation: Transients in Fossil and Nuclear Power Plants."

Because recorded transient data were already available on nuclear plants, no special power plant testing was performed to validate nuclear modules. A model of the Three Mile Island (TMI) reactor coolant system and its once through nuclear steam generators was validated against two recorded transients, one in TMI-1 and the other in TMI-2. A turbine trip transient had also been recorded under EPRI contract in Arkansas Nuclear One Unit 2. This transient was simulated with a model containing the same reactor and pump modules as the TMI model, but with a U-tube steam generator and a different pressurizer module. These validations are also reported in EPRI CS/NP-2945.

Usability

To confirm the usability of the code, and to provide an opportunity to identify and correct any shortcomings in ease of use or documentation, a prerelease users group was established consisting of 8 utility members of EPRI in February 1982. One utility was added to the group the following autumn. The members were provided with draft user documentation and given a three day training course in the use of MMS. They were provided continuing consultation (largely by telephone) when needed to resolve difficulties. The overall results were favorable. All but the last user to joining the group completed a model and produced transient simulations before the end of the trial use period. One member used the results to devise a correction for an unsatisfactory heater drain pump and drain tank control in a nuclear plant. Two others used it to determine how best to proceed in the procurement of control systems, one for a new design plant and one for a major retrofit. Reports by the users group members are included in the proceedings of the Modular Modeling System (MMS) Code Release Workshop, held April 20-22, 1983 in Charlotte, North Carolina.

Engineering effort required to prepare and use a model must, of course, be judged in conjunction with the size of the model. Only two models covered the entire plant. They averaged 1800 engineering hours for the entire effort. The modelers believed they would require fewer hours for a second model of the same size. Computer costs, too, are a function of both size of model and experience in using the MMS. They are also a function of the billing rate to the particular user, even

when all are using the same service bureau. This is because the billing rate per unit of computation decreases as total company usage increases. For the complete plant models the computer cost on a service bureau computer averaged about $8000 during this first time use.

During the course of their work, the users group members identified the need for a number of additional specialized modules, which were provided. Most are being added to the permanent module library. They also provided an excellent practical review of the documentation. Their comments are incorporated in the final Computer Code Manual, of which this report reproduces a part.

Some users group members also ran into an unexpected and time-consuming difficulty resulting from the definition of the problem to be solved and the boundary conditions used. In several cases, users inadvertently modeled situations which could not occur in an actual plant. They obtained unexpected and puzzling results because the model had, in effect, provided a correct answer to an incorrect question. Because the cause of their difficulty was not obvious (and some of the features that made the models unrealistic were quite subtle), they spent considerable time searching for bugs in the program. While the modeling process provides insight into behavior of the plant, it also demands an understanding of what is reasonable to expect and what is not -- that is, physical insight. It is believed that engineers familiar with plant design and operation are those most likely to have such insight. Suggestions have been added to the user manual on how to avoid improper definition of problems, but in the end this will depend on the physical insight of the user.

CONCLUSION

The MMS provides a modeling capability which makes it suitable for insertion in the iterative process of plant design and plant troubleshooting, as well as for performing a number of other functions. Its suitability and usability have been demonstrated by actual testing. MMS-01 is ready for installation on licensees' in-house computers or for their use on a service bureau computer. MMS-02 is also ready for use, but only on a service bureau computer under prerelease licensing agreement with EPRI.

MODULAR MODELING SYSTEM

THEORY MANUAL

PART I

OVERVIEW

PART I

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Section 1

INTRODUCTION

The Modular Modeling System (MMS) is a simulation code for modeling the dynamic performance of nuclear or fossil fueled electric power plants. The modeling system has the potential of being used by the electric utility industry during plant design and operation for improving plant performance. It is intended that the MMS code should assist utility engineers and operation personnel with:

- specification, selection, and integration of plant components;

- design and checkout of control systems,

- rapid simulation to expedite plant commissioning;

- improved diagnosis of plant performance.

- best estimate plant safety analysis,

- plant simulator qualification, and

- procedure evaluation.

The main problems that have prevented the widespread use of dynamic modeling are (i) high cost, especially for engineering time, (ii) the specialized skills and experience required from the user; (iii) the long lead time required to produce a dynamic model; (iv) the lack of confidence in the validity of the model. To be effective, a dynamic modeling tool must be readily usable by both design engineers and professional modelers; therefore, it should be simple, flexible and modular, economic and sufficiently accurate for the analysis of both operational and long term off-normal transients.

The MMS addresses these objectives and problems by means of its basic modularity concept and the careful design of its elements, including module formulations, parameterization, integration and analysis methods, run time procedures and validation tests. In the following sections the basic concepts and elements of MMS will be described.

Summarizing the fundamental characteristics and theoretical basis of MMS:

OVERALL FEATURES

- The MMS library documented in this revision of the Theory Manual consists of 40 modules representing most components used in conventional fossil-fueled and pressurized water reactor (PWR) nuclear power plants. These include balance of plant (BOP) type components (pipes, valves, pumps, feedwater heaters, steam turbines, flash tanks and condensers), fossil boiler components (furnaces, superheaters and attemperators), and nuclear components (PWR reactors, pressurizer and steam generators).

- In addition to the library of modules documented in this revision of the Theory Manual, modules have been developed that will simulate the two-phase flow needed to perform nuclear plant accident analysis, and others that will simulate the nuclear steam supply components of a boiling water reactor (BWR). These modules are being tested by a Trial User Users Group and will not be released for general use until the trial period is completed. However, they are documented in draft form in the same format as the modules in this manual.

- The modules may be interconnected in any possible arrangement. All variables are automatically generated with names suggesting the engineering quantity represented (T for temperature, H for enthalpy, W for flowrate, etc.)

- All modules are completely self-contained and may be removed and another module substituted without affecting coding for any other module.

- The MMS steam property library contains 40 FORTRAN routines which efficiently calculate ASME steam properties.

- MMS is written in high level dynamic simulation languages. It is available in two versions, the Advanced Continuous Simulation Language (ACSL) developed and supported by Mitchell & Gauthier and Associates, and EASY5 developed and supported by Boeing Computer Services, Inc. These languages serve as a pre-processor to convert the user program, written in one of the languages, into a FORTRAN program. They both provide extensive user convenience features for input/output like line or print plotting. The languages also provide sophisticated integration algorithms and linear analysis routines.

THERMOHYDRAULIC BASIS

- All thermohydraulic calculations performed as part of MMS have a firm basis in first principles based on conservation of mass, energy, and momentum, and the second law of thermodynamics. In many cases, simplifying assumptions are made within a particular module to enhance model economy. In all cases where these assumptions are made, they are clearly identified in the module documentation.

- MMS provides multiple versions of some modules distinguished by the simplifying assumptions used in their development, and therefore their range of application, and by their economy of operation.

- The "single-phase" modules, principally BOP and fossil modules, either assume that the fluid phase is known, or that phase equilibrium exists.

- Where it is necessary to accurately represent component dynamics, as in an NSSS pressurizer, the formulations provide for possible phase non-equilibrium.

- The "two-phase" modules, principally NSSS primary loop modules, are applicable for either single or two-phase conditions and use drift-flux formulations to account for reverse flow, level tracking, counter-current flow, and flooding. Just as in the "single-phase" modules, where necessary, the formulations provide for phase non-equilibrium.

- All modules use a lumped parameter formulation. Some modules are formulated on the basis of fixed volume nodes and some use a moving boundary scheme.

FLUID MECHANICS AND HEAT TRANSFER

- Fluid mechanics and heat transfer relations are based largely on empirical or semi-empirical forms.

- In general, for reasons of economy, the module formulations do not include the full relations for heat transfer coefficients and fluid resistances. Rather, only the form and the dominant term or terms are retained together with a user-calculated parameter which includes property variations and other secondary terms. The module then calculates the variation of the heat transfer coefficient or fluid resistances from its value at the point at which it was parameterized.

- For heat transfer formulation, the "single-phase" modules use the Dittus-Boelter correlation for fully developed turbulent flow inside tubes, a Babcock & Wilcox formulation for fully developed flow of gases outside tubes, Stefan-Boltzmann for gas radiation, Thom for nucleate and bulk boiling, and a Westinghouse correlation for film condensation on horizontal feedwater heater tubes.

NUMERICAL INTEGRATION AND LINEAR ANALYSIS

- All modules are formulated to generate a set of explicit first order ordinary differential equations as required.

- A central integration technique is used as opposed to a finite difference scheme.

- Several numerical integration methods are available in both the ACSL and EASY5 versions. Both explicit and implicit methods may be used but in most cases the Gear variable-step-size, variable-order

algorithm is the method of choice for the stiff equations character-
istic of power plant models.

● Linear analysis capabilities greatly enhance the applications of MMS.
Routines available in both versions of MMS include:

(1) steady state finder

(2) linear model

(3) eigenvalue and eigenvector

Routines presently available only in the EASY5 version include:

(1) stability margin

(2) root locus

(3) Nyquist plots

(4) Bode plots

(5) optimal control

Table 1-1 summarizes the available single-phase component modules and Table 1-2
summarizes the available two-phase modules. Section 4 of this manual summarizes the
characteristics of the modules and their applications to date.

Table 1-1

MMS SINGLE PHASE MODULES

MODULE DESCRIPTION	ACSL NAME	EASY5 NAME	COMMENTS
BALANCE OF PLANT COMPONENTS			
Condenser	CONDEN	HN	Equilibrium model; non-condensables neglected; level calculation
Water-to-Water Heat Exchanger	COOLER	HC	Heat transfer by convection; counter-flow or parallel-flow
Deaerator	DEAER	DA	Equilibrium mixing tank model; non-condensable neglected; level calculation
Flash Tank	FLASH	FT	Level calculation; equilibrium model
Closed Feedwater Heater	FWHTR, CONFIG-1	FH	
	CONFIG-2	F2	Drain cooling and/or desuperheating regions
	CONFIG-3	F3	optional; level calculation; flooding and
	CONFIG-4	F4	non-condensables neglected
Pipes - Steam/Resistive-Storage	PIPESC	SC-SS	Inertia, metal thermal storage and losses,
- Steam/Resistive	PIPESR	SR-SP	transport delay optional
- Water/Resistive-Storage	PIPEWC	WC-WS	
- Water/Resistive	PIPEWR	WR-WP	
Variable Speed Motor Driven Pump	PUMPHC	PH	Head-flow characteristics modeled;
Constant Speed Motor Driven Pump	PUMPMD	PM	cavitation, leakage, seal injection and
Steam Turbine Driven Pump	PUMPTD	PT	cooling neglected; single extraction, driven by single or dual pressure source
High Pressure Steam Turbine	TURBHP	TH	Multi-valve operation; extraction, reaction and impulse blading performance; variable speed

Table 1-1 (Cont.)

MMS SINGLE PHASE MODULES

MODULE DESCRIPTION	ACSL NAME	EASY5 NAME	COMMENTS
LP/IP Steam Turbine	TURBLP	TL	Reaction blading, extractions and moisture removal modeled; variable speed; exhaust losses
Valves - Steam	VALVEC	VC	Modulation with optional valve characteristics; choking modeled
- Dump	VALVED	VD	Flashing characteristics; modulation
- Water	VALVEI	VI	Modulation with optional valve characteristics; piping effects considered
CONTROL COMPONENTS			
Valve Actuator	ACT	AC	
On-Off Controller	ONOFF	GF	Deadband
P-I Controller	PICONT	GP	Anti-reset windup
FOSSIL COMPONENTS			
Steam to Air Heat Exchanger	AIRHX	HA	
Spray Attemperator	ATTEMP	AT	
Forced Circulation Furnace	DRUMFC	BF	Shrink and swell; variable burner tilts
Natural Circulation Furnace	DRUMNC	BN	Shrink and swell; variable burner levels
Economizer	ECON	EC	Heat transfer by radiation and connection
Once-Through Supercritical Furnace	OTBLR	BO	Applicable sub or supercritical, enclosures addressed
Pulverizer	PULV	CP	

Table 1-1 (Cont.)

MMS SINGLE PHASE MODULES

MODULE DESCRIPTION	ACSL NAME	EASY5 NAME	COMMENTS
Regenerative Air Heater	REGHX	HR	User specified speed
Superheater	SPRHTR	HS	Heat transfer by radiation and convection
NUCLEAR COMPONENTS			
Moisture Separator Reheater	MSRHT	HM	Equilibrium model; cross-over steam heat transfer, drain tank level modeled
Once-Through Steam Generator	OTSGEM	HO	Secondary side: moving boundary model with subcooled, boiling and superheating regions Primary side: single-phase sub-cooled liquid
Pressurizer	PRESZR	Z1	Non-equilibrium model; operates from full to empty
PWR Reactor - 3 Node	RX3	R3	1-D, three axial nodes; prompt-jump approx; 3 delayed groups; xenon
- 12 Node	RX12	RT	Four quadrant; assymmetric conditions
Surge Junction	SURJNC	JS	Bi-directional flow in and out of pressurizer
U-Tube Steam Generator	UTSGR	HU	Similar to OTSG in formulations; drift flux for void fraction calculations

Table 1-1 (Cont.)

MMS SINGLE PHASE MODULES

MODULE DESCRIPTION	ACSL NAME	EASY5 NAME	COMMENTS
JUNCTION AND CONNECTIVE COMPONENTS			
Connective - Steam	CONNC	CC	
- Water	CONNI	CI	
Flow Divider	DIV	D2-D8	
Flow Junction	JUNC	J2-J8	

Table 1-2

MMS TWO-PHASE MODULES

MODULE DESCRIPTION	ACSL NAME	EASY5 NAME	COMMENTS
Pipe	PPTP	PI	Drift flux two phase; momentum optional
Pressurizer	PZRTP	PR	Non-equilibrium; vapor, mixture, or solid
Steam Generator (U-Tube)	UTSGTP	UT	Drift flux on primary and secondary, secondary vapor, mixture, or solid;
Steam Generator (Once-Through)	OTSGTP	OG	tube rupture; level tracking; flooding
Reactor - Neutronics	NUTRON	NU	Point kinetics; void reactivity feedback; three axial nodes
- Upper Plenum and Head	UPLNTP	RU	Non-equilibrium; level tracking
- Lower Plenum and Core	LPLNTP	RL	Level tracking; drift flux
Variable Speed Pump	PMPVTP	PC	Four quadrant operation; two phase
Critical Flow	CRITTP	SR	Moody/Henry-Fauske model
Merge	MERGE	ME	
Split	SPLIT	SL	

Section 2

MODULARITY CONCEPT

The foundation of the MMS is the modularity concept which permits a system model to be built using independently developed component models (modules). Each module is required to completely describe a physical plant component to the prescribed level of fidelity and to be independent of any other adjacent module. The MMS can represent any model described by a set of ordinary differential and algebraic equations, from a coal pulverizer to a non-equilibrium two-phase nuclear reactor. Different modules may be defined to describe the same physical component to different levels of depth and complexity as required by the specific purpose of the simulation. The equations of each module must be compatible with other modules, the module parameters must be readily derived from available data on the physical component, and finally, an adequate set of modules (library) must be available to represent an entire plant.

The modularity concept has been extended to include the system analysis and integration packages used by the MMS. In this way it is possible to modify, replace, or add new integration algorithms and analysis capabilities (e.g., eigenvalues, transfer functions, stability margin, etc.) without any change in the modules themselves. The main advantages of the modularity concept are:

1. Model complexity defined by performance requirements;

2. Freedom to model "any" system, subsystem, or physical process;

3. Parameterization requirements defined by module;

4. Art of modeling reduced for general user;

5. Built-in validity checks;

6. Accumulated knowledge by use of standard modules and benchmarking;

7. Easy and inexpensive possibility to modify the model by replacing modules and changing parameters.

It is believed that the modularity concept combined with the automatic analysis functions provided by MMS can reduce the specific skills required of the user and decrease the cost and effort needed for dynamic modeling.

Section 3

MMS ELEMENTS

There are four basic elements of MMS: library of modules, framework, analysis packages, and modeling methodology which will be discussed below.

3.1 LIBRARY OF MODULES

The Modular Modeling System contains a library of pre-engineered models (called modules) of each major type of component in a power plant. From this library, a User may construct a model of great simplicity or great complexity, depending on the objectives of the simulation. Each module is pre-validated to foster confidence in the results.

Many of the MMS modules are flexible (e.g., valve characteristics may be changed from linear to quick opening between runs), while others (e.g., reactor and steam generator) are vendor specific. New modules can and will be added to the MMS library by both the developers and the users.

3.2 MMS FRAMEWORK

The modularity concept of MMS is implemented in two software systems (simulation languages); (1) Advanced Continuous Simulation Language (ACSL), developed and supported by Mitchell and Gauthier, Assoc., and (2) EASY5, developed and supported by Boeing Computer Services Company. Both languages comply with the modularity concepts, provide the basic functions needed for MMS implementation, and can be installed on most large computers and many smaller machines. They are also available through remote terminal access to commercial time-share computers. These systems provide two functions. As a precompiler (translator) for the model, they greatly reduce most of the time-consuming and error prone tasks. They also provide a run time executive that performs the analyses and directs outputs to various devices.

Figure 3-1 shows the MMS framework which includes the user's program or source code that is input to the ACSL/EASY5 precompiler. After checking for syntax errors the
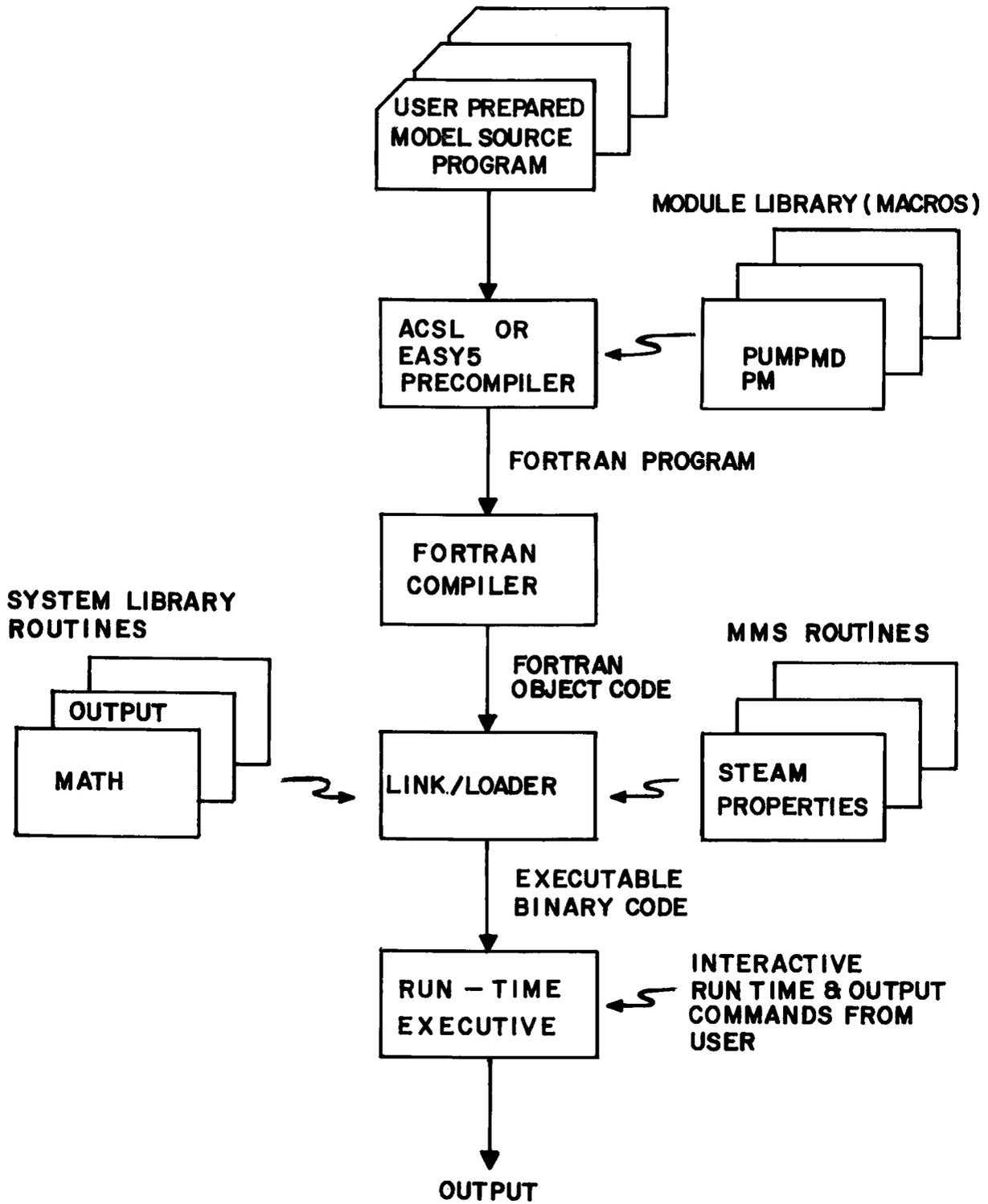
3-1

Figure 3-1. MMS Structure

precompiler constructs a complete FORTRAN program which includes the replacement of all on-line module calls in the user's program by the complete set of equations from the library MACRO, sorting the equations into a computable order, identifying missing parameters and implicit loops. The FORTRAN source code generated by the precompiler is compiled to generate a FORTRAN object code which is linked together with different system routines (mathematics, outputting, etc.) and MMS routines such as steam property algorithms. The executable binary code produced by the loader is then ready to run. The run-time executive enables the user to change component parameters at run time, thus adding flexibility to execution of the code. In addition, different types of analyses for the dynamic system are available.

MMS is formulated and designed to use central integration to solve the system of first order ordinary differential equations (ODE's) generated by the modules. Central integration is used instead of an equation-by-equation finite difference approach because of the availability of very efficient integration techniques included within MMS.

In general, the simulation of a power plant generates a stiff set of ODEs. Classically, a stiff set of equations is a set whose range of eigenvalues, or range of time constants, is greater than three orders of magnitude. This complicates the numerical integration because the time step of integration with explicit algorithms must be very small to accommodate the fast eigenvalues (short time constants). This is particularly unfortunate because the user is not usually interested in a range of dynamics this large. In fact, this constitutes the practical definition of stiffness: A model is stiff if it has dynamics faster than those in which the user is interested. If an explicit method is used to integrate a stiff model, simulation costs will be high because time steps must be small to follow the fast dynamics.

To efficiently solve a stiff system of equations on a digital computer requires an implicit integration algorithm. The most popular algorithm of this type is commonly referred to as a Gear algorithm (or a modification of it) named after Professor C.W. Gear who developed one of the first useful implicit algorithms. The reasons for the superiority of implicit algorithms for stiff systems is beyond the scope intended here, but it is important to note that a steam generation process model is, in reality, a stiff system of equations. The equations can be manipulated to make a model that is not as stiff as the process but not without compromising modularity.

3.3 ANALYSIS PACKAGES

In addition to the simulation capability of the MMS, several analysis packages are provided in each simulation language which enable the computation of steady state (initial conditions), eigenvalues and their sensitivity and linear model approximation. In addition, the EASY5 version provides transfer functions, root locus, stability margin, and optimum controller design. These linear analysis methods can be used for the highly non-linear plant models typically studied with MMS, provided the models are continuous.

3.4 MODELING METHODOLOGY

Modeling methodology includes the rules and procedures for developing modules and building a plant model with MMS. The module development rules assure that independently developed modules will be compatible with both other modules and the analysis routines. The plant modeling rules establish the way in which a complete model is built of existing modules, including correct interconnections and parameterization.

The MMS nomenclature provides the following functions: (i) generation of variable names; (ii) preventing name conflicts between modules; (iii) provision for automatic module interconnections; (iv) facilitating input and output.

Module compatibility is guaranteed by use of the MMS nomenclature and the concept of Resistive and Storage modules. Modules are characterized on the basis of their pressure-flow formulation. This is the primary concern in generating compatible modules. For instance, a valve is naturally described by its flow rate, as determined by the difference between the pressures acting on its upstream and downstream sides. It is characterized as Resistive. A flash tank is basically an accumulator; the rate of change of its presure, and perhaps level, determined by the flow rates at each port. It is characterized as a Storage type. A convenient means of connecting Resistive modules is also provided through the use of the MMS Connective node. With these types of components, any model may be constructed with the simple guideline that Resistive modules must alternate with Storage or Connective modules in the flow path.

A comprehensive User's Manual provides step-by-step instructions for model generation and execution. User worksheets for each module direct the user to required

vendor data for module parameterization. These convenience features are intended to substantially reduce engineering time and costs and, thereby, reinforce the MMS philosophy.

Section 4

SUMMARY OF MODULE CHARACTERISTICS AND APPLICATIONS

This section provides a summary of characteristics of the MMS modules, that is the physical effects simulated, limitations, and range of operation, and a list of the applications of each module to date. The module summary is included in Paragraph 4.1 and the summary of applications in Paragraph 4.2.

4.1 SUMMARY OF MODULE CHARACTERISTICS

The characteristics and capabilities of each of the MMS modules is summarized in the following pages. The modules are identified by ACSL Name/EASY5 Name.

SINGLE PHASE MODULES

BALANCE OF PLANT MODULES

MODULE SUMMARY: CONDEN/HN

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Heat transfer between steam and cooling water	• Non-equilibrium effects	• Reverse cooling water flow	• Level between dry and flooded tubes
• Changes in condenser level due to net mass flow	• Effects of non-condensable gases	• Level out of bounds	
• Fouling			

MODULE SUMMARY: COOLER/HC

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Heat exchange by forced convection on shell and tube sides	• Reverse flows	• Reverse flow on tube side	• Steam property limited
• Flow resistance on shell and tube sides	• Energy storage in tube metal	• Reverse flow on shell side	
	• Boiling		
	• Two-phase flow		

MODULE SUMMARY: DEAER/DA

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity checks	Range of Operation
• Feedwater heating by deaerating steam	• Effects of non-condensable gases	• Level out of range	• Steam property limited
• Feedwater storage	• Non-equilibrium effects		
• Elevation head			
• Equilibrium			

MODULE SUMMARY: FLASH/FT

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Energy and Mass Storage	• Non-physical drawdown	• High level	• Steam property Limited
• Liquid Level (if present)	• Solid Operation		
• Equilibrium conditions	• Ideal Steam/water separation when liquid level present		
• Elevation head on drain leaving			

MODULE SUMMARY: FWHTR/FH,F2,F3,F4

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Heat transfer between steam and feedwater	• Non-equilibrium effects	• Reverse feed-water flow	• Level between dry and flooded tubes
• Drain cooling and/or desuper-heating	• Heat transfer in flooded heater	• Level out of bounds	
• Changes in heater level due to net mass flow	• Effects of non-condensable gases		
• Fouling			

MODULE SUMMARY: PIPE MODULES

PIPESC, PIPESR, PIPEWC, PIPEWR

SC-SS, SR-SP, WC-WS, WR-WP

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Pressure losses from friction and elevation losses	● Two-phase flow	● Reverse flow	● Steam property limited
	● Compressibility effects		
● Inertia	● Reverse flow		
● Energy storage in fluid and pipe metal			
● Fluid expansion			
● Transport delay			
● Heat loss to ambient			

MODULE SUMMARY: PUMPHC/PH

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
● Variable speed pump head-flow characteristics	● Cavitation	● Reverse flow of feedwater	● Steam property limited
● Pumping power input to system	● Leakage	● Require pump speed greater than driver speed	
	● Seal injection		
	● Seal cooling		
	● Windmilling		
	● Reverse flow		

MODULE SUMMARY: PUMPMD/PM

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
• Pump head-flow characteristics	• Cavitation	• Reverse flow	• Steam property limited
• Pumping power input to system	• Pump startup and coastdown		
	• Variable speed		
	• Extractions		
	• Leakage		
	• Seal injection		
	• Seal cooling		
	• Windmilling		
	• Reverse flow		

MODULE SUMMARY: PUMPTD/PT

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
• Variable speed pump head-flow characteristics	• Cavitation	• Reverse flow of feedwater	• Steam property limited
• Pumping power input to system	• Leakage		
• Single extraction	• Seal injection		
• Steam turbine driver with single or dual pressure source	• Seal cooling		
	• Windmilling		
	• Reverse flow		

4-6

MODULE SUMMARY: TURBHP/TH

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
● Multi-valve operation	● Variable speed calculated elsewhere	● None	● Steam property limited
● Impulse and reaction blading performance	● Valve drains		
● Extractions	● Metal temperatures		
● Effect of speed changes on performance	● Sealing steam		

MODULE SUMMARY: TURBLP/TL

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Reaction blading performance	● Variable speed calculated elsewhere	● None	● Steam property limited
● Extractions	● Metal temperatures		
● Exhaust losses	● Sealing steam		
● Effect of speed on efficiency			
● Moisture Removal			

MODULE SUMMARY: VALVEC/VC

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Frictional and acceleration pressure losses for dry steam	• Adiabatic	• Reverse flow	• Fully open to fully closed
	• Two-phase flow		
• Choked flow	• Quasi-steady state		
• Valve modulation with optional valve characteristics	• Reverse flow		
	• Packing effects		

MODULE SUMMARY: VALVED/VD

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Frictional and acceleration losses for single phase water	• Adiabatic	• Reverse flow	• Full open to full closed
	• Quasi-steady state		
• Frictional pressure loss characteristics for flashing	• Reverse flow		
	• Packing effects		
• Choking			
• Valve modulation with optional valve characteristics			

MODULE SUMMARY: VALVEI/VI

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Frictional pressure losses for single phase water due to valve and associated piping	• Adiabatic	• Reverse flow	• Fully open to fully closed
• Valve modulation with optional valve characteristics	• Flashing or cavitation		
	• Quasi-steady state		
	• Packing effects		

SINGLE PHASE MODULES

CONTROL MODULES

MODULE SUMMARY: ACT/AC

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● First order lag type response	● Undersized actuator	● None	● 0 to 100 open
● Rate limited resonse	● Rigorous physics		

MODULE SUMMARY: PICONT/GP

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Proportional plus integral control		● None	● Unlimited
● Anti-reset windup			

MODULE SUMMARY: ONOFF/GF

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● On-off type control with deadband		● None	● Unlimited

SINGLE PHASE MODULES

FOSSIL MODULES

MODULE SUMMARY: AIRHX/HA

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Heat exchange between air, metal, and steam/water	• Reverse flow	• Reverse flow limited	• Steam property
• Energy storage in tube metal	• Air pressure-flow dynamics		
• Air temperature variation within moisture content	• Air dew point		
• Simplified two-phase flow calculations			

MODULE SUMMARY: ATTEMP/AT

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Ideal mixing of two flow streams	• Flashing or compressibility effects in control	• Reverse flow in steam path	• Spray valve position; 0-100 percent open
• Operation of spray control valve and effect of attached piping	• Compressibility effects on steam path pressure losses	• Reverse flow in spray path	• Steam property limited
	• Non-ideal mixing		
	• Reverse flows		

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MODULE SUMMARY: DRUMFC/BF

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Heat absorption to fluid by radiation	• Reverse flow	• Drum level out of limits	• Steam property limited
• Heat loss to atmosphere	• Flooded nozzles		• Drum level between 0 and flooded
• Heat absorption changes due to gas recirculation	• Tube leaks		
• Heat absorption changes due to change in air/fuel	• Gas side pressure dynamics		
	• DNB		
• Heat absorption changes due to slag build up and removal	• Individual tube temps		
• Heat absorption change in furnace due to burner tilt	• Combustion chemistry		
	• Non-equilibrium effects		
• Heat absorption changes due to change in type fuel being burned			
• Heat absorption changes due to changes in fuel BTU content and coal moisture			
• Water level shrink and swell due to pressure and heat absorption changes, and drum water inventory			
• Heat absorption and drum level changes due to number of recirculation pumps in service			

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
● Heat absorption to fluid by radiation from flame	● Reverse flow	● Drum level out of limits	● Steam property limited
● Heat loss to atmosphere	● Flooded nozzles		● Drum level between 0 and flooded
● Heat absorption changes due to change in air/fuel	● Tube leaks		
● Heat absorption changes due to slag build up and removal	● Gas side pressure dynamics		
	● DNB		
● Heat absorption change in furnace due to number of burner levels in service	● Individual tube temps		
	● Heat absorption distribution		
● Heat absorption changes due to change in type fuel being burned	● Combustion chemistry		
	● Non-equilibrium effects		
● Heat absorption changes due to changes in fuel BTU content and coal moisture			
● Water level shrink and swell due to pressure and heat absorption changes, and drum water inventory			

MODULE SUMMARY: ECON/EC

Physical Effects to Be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
• Heat exchange between flue gas and water	• Tube leaks	• Reverse flows	• Limited by properties
• Changes in heat absorption due to slagging	• Individual tubes		
• Energy storage in flue gas and water	• Boiling		
• Gas temperature variation with moisture content	• Gas pressure dynamics		
• Heat storage in metal mass			

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
● Heat absorption to fluid by radiation from flame	● Reverse flow	● None	● Steam property limited
● Heat loss to atmosphere	● Tube leaks		
● Heat absorption changes due to gas recircula- tion	● Gas side pressure dynamics		
	● DNB		
● Heat absorption changes due to change in air/ fuel ratio	● Individual tube temperatures		
	● Heat absorption distribution		
● Heat absorption changes due to slag build up and removal	● Combustion chemistry		
	● Non-equilibrium effects		
● Heat absorption change in furnace due to number of burner levels in service			
● Heat absorption changes due to change in type fuel being burned			
● Heat absorption changes due to changes in fuel BTU content and coal moisture			
● Heat absorption from other modules			
● Heat loss to other modules			

MODULE SUMMARY: PULV/CP

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Coal storage, grinding, and flow to burners	● Mill choking due to moisture not included	● Primary air flow < 50%	● Model is scaled
● Motor current	● Mill fires not modeled	● Coal storage > 150% normal full load storage	
● Mill pressure drop	● Primary air flow is treated as an input		
● Mill outlet temperature			

MODULE SUMMARY: REGHX/HR

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Heat exchange between gas and rotor and rotor and air	● rotor is assumed to be in motion. Model is not valid at zero speed	● None	● Rotational speed above 10 revolutions per hour
● Energy storage in rotor	● Moisture condensation and corrosion effects are not modeled		
● Air and gas temperature variation with moisture content	● Pressure drop across unit is not calculated		
ɔ Exchange of air and gas due to seal sectors			

MODULE SUMMARY: SPRHTR/HS

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
• Heat absorption between gas, metal, and fluid	• Tube leaks	• Reverse flow	• Steam property limited
• Changes in heat absorption due to slagging and removal of slag	• Individual tubes		
• Mass/Energy storage in fluid side of exchanger. Energy storage in gas side	• Reverse flows		
• Gas temperature variation with gas moisture content	• Gas pressure dynamics		
• Heat storage in metal mass	• Boiling		

SINGLE PHASE MODULES

NUCLEAR MODULES

MODULE SUMMARY: MSRHT/HM

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
• Changes in drain tank level due to net mass flow	• Non-equilibrium effects	• Level in tank out of bounds	• Steam property limited
• Tube fouling	• Effects of non-condensable gases	• Complete condensation of reheat steam	
• Heat transfer to crossover steam	• Reverse flow	• Reverse flow in tube side of reheaters	
• Moisture removal from crossover steam	• Compressibility effects		

MODULE SUMMARY: OTSGEM/HO

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
• Heat transfer from the primary to the secondary by convection on the primary side and liquid convecton, bulk boiling, and steam convection on the secondary	• Reverse flows	• Two-phase flow entering primary	• Full range of steam properties
	• Secondary pressure losses	• Two-phase flow entering secondary	
	• Drift flux	• Reverse flow in primary	
• Primary frictonal pressure losses	• Film boiling	• Low/High liquid level in secondary side	
• Energy storage on the primary and secondary side			
• Density head on the primary side			

MODULE SUMMARY: PRESZR/Z1

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
● Non-equilibrium conditions	● Solid vessel	● Level	● Steam property limited
● Droplet rainout, bubble rise	● Zero liquid level		● Level from zero to full
● Condensation on walls and liquid-vapor interface	● Heat loss to atmosphere		
● Bi-directional flow path from primary loop	● Supercritical pressure		
● Connection for spray, and relief valve			
● Heaters			

4-22

MODULE SUMMARY: RX3/R3

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
• Neutron kinetics (3 distributed nodes)	• No two-phase conditions	• Reverse flow at inlet	• Pressure from 15 psia to 3200 psia
• 3 delayed neutron groups per node	• No reverse flow		• Subcooled only
• 3 decay heat groups per axial level	• Maximum of 4 inlets and 2 outlets		
• Xenon dynamics	• No fuel pin dynamics		
• 5 rod groups			
• Adjustable upper and lower plenum mixing			
• Out-of-core detectors			

- geometry effects
   - calibration
   - temperature effects
   - offset			

• Boron concentration			
• Density head (for natural circulation)			

MODULE SUMMARY: RX12/RT

Physical Effects to be Modeled	Limitations and/or Effects Not Included	Validity Checks	Range of Operation
● Neutron kinetics (12 distributed nodes)	● No two-phase conditions	● Reverse flow at inlet	● Pressure from 15 psia to 3200 psia
● 3 delayed neutron groups per node	● No reverse flow		● Subcooled only
● 3 decay heat groups per axial level	● Maximum of 4 inlets and 2 outlets		
● Xenon dynamics	● No fuel pin dynamics		
● 5 rod groups	● No DNBR calculation		
● Rod malfunction			
● Adjustable upper and lower plenum mixing			
● Out-of-core detectors - geometry effects - calibraton - temperature effects - offset - imbalance			
● Boron concentration			
● Density heat (for natural arc)			

MODULE SUMMARY: SURJNC/JS

Physical Effects to be Modeled	Limitations and/or Effects Not Simulated	Validity Checks	Range of Operation
● Bi-directional flow into or out of the pressurizer	● Two-Phase flow	● None	● Steam property limited

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Heat storage in tube metal included	• Reverse flow on the primary	• Two-phase flow entering on primary side	• Full range of steam properties
• Heat transfer from primary to metal by liquid convection	• Primary fluid in two-phase conditions	• Two-phase flow entering on secondayr side	• Hot stand by to beyond full load operations
• Heat transfer from metal to secondary by liquid convection in subcooled nodes and bulk boiling in boiling nodes	• Feedwater in two-phase conditions	• Reverse steam flow	
• Pressure drop due to frictional losses, acceleration losses and from losses on secondary side	• No steam flow or feedwater flow. Only subcooled heating, or only saturated boil-on secondary side	• No steam flow	
• Pressure drop due to frictional losses on primary side	• Film boiling	• Secondary side is mostly single-phase liquid in heated region	
• Density head on the primary side		• Secondary side is mostly two-phase in heated region	
• Drift flux formulation for vapor fraction calculation on secondary side			

TWO-PHASE MODULES

MODULE SUMMARY: PPTP/PI

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Drift-flux treatment of two-phase flow	• Multi-dimensional flow	• None	• Steam property limited
• Subcooled liquid or superheated vapor	• Critical flow		
• Optional fluid momentum	• Non-equilibrium effects		
• Counter current flow			
• Flooding			
• Reverse flow			
• Energy storage in walls and heat loss to ambient			
• Laminar and turbulent flow correlations			

MODULE SUMMARY: PZRTP/PR

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Drift flux treatment	● Stratification in liquid	● None	● Steam property limited
● Non-equilibrium effects	● Subcooled boiling		
● Applicable for solid (all liquid) or empty (all vapor)			
● Condensation on walls and at liquid-vapor interface			
● Bi-directional single or two-phase flow to or from primary			
● Spray valve and relief valve			
● Heaters			
● Heat loss to ambient and heat storage in walls			

MODULE SUMMARY: OTSGTP/OG

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Heat transfer between primary and secondary by subcooled or super-heated convection bulk boiling or post dry-out	• Non-equilibrium effects	• None	• Steam property limited
• Drift flux treatment of two-phase flow	• Auxiliary feed at top of tube bundle		• Secondary side cannot be water solid
• Level tracking on primary	• Recirculation		
• Tube rupture			

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Heat transfer between primary and secondary by subcooled or superheated convection (laminar or turbulent), subcooled boiling, bulk boiling, or post dry-out	• Non-equilibrium effects	• None	• Steam property limited
• Drift flux treatment of two-phase flow on both primary and secondary			
• Energy storage in tubes			
• Tube rupture			
• Multi-tube representation			
• Level tracking in each tube and on secondary			
• Reflux boiling in each tube			
• Recirculation by natural circulation			
• User specified carryover/carryunder			

MODULE SUMMARY: PMPVTP/PC

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Four quadrant representation of centrifugal pump based on homologous curves	• Cavitation	• None	• Steam property limited
	• Leakage		
• Two-phase flow	• Seal injection		
• Coast down	• Seal cooling		
• Frictional heating			

MODULE SUMMARY: CRITTP/SR

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
• Moody/Henry-Fausky critical flow	• Shock wave propagation upstream only	• None	• Steam property
• Optional tracking of shock front in one direction			
• Reverse flow in normal (non-critical) flow conditions			

MODULE SUMMARY: NUTRON/NU

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Neutron kinetics (3 distributed axial nodes)	● Prompt criticality	● None	● Steam property limited
● Three delayed neutron groups per node			
● Three decay heat groups per axial level			
● Optional xenon dynamics			
● Five rod groups			
● Out-of-core detectors			

- geometry effects
   - calibration
   - temperature effects
   - offset			

● Boron concentration effect			
● Void effects on reactivity			
● 2 Radial node fuel pin			

MODULE SUMMARY: UPLNTP/RU

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Mass and energy dynamics using drift flux treatment	● Non-equilibrium conditions	● None	● Steam property limited
● Equilibrium 2-phase conditions possible from heat to bottom of core			
● Vapor separation from main flow stream - collects in vessel head to cause bubble			
● Energy dynamics in head metal			

MODULE SUMMARY: LPLNTP/RL

Physical Effects to be Modeled	Limitations and/or Effects Not Modeled	Validity Checks	Range of Operation
● Downcomer and lower plenum	● Radial asymmetry	● None	● Steam property limited
● Three node model of core thermal hydraulics using drift flux treatment	● Fluid mixing/ asymmetry		
● Level tracking			
● By-pass flow			

4.2 SUMMARY OF APPLICATIONS

This paragraph summarizes the application of the single-phase and two-phase modules as of February 1983. To date, the single-phase analyses have utilized the ACSL version and the two-phase analyses have utilized the EASY5 version.

BALANCE OF PLANT MODULES - ACSL Version

APPLICATION (columns, left to right):

1. Grand Gulf Nuclear-1 (Middle South Services)
2. Mystic 7 (Bechtel)
3. Mystic 7 (Babcock & Wilcox)
4. Potomac River-3 (PEPCO)
5. Lansing Smith-2 (Southern Company Services)
6. Wilton-1 (Middle South Services)
7. Fermi-2 (Detroit Edison)
8. TMI (General Public Utilities)
9. San Onofre-2 (Southern Calif. Edison)
10. TMI (B&W)
11. Arkansas Nuclear 1-2 (Systems Control)
12. Robinson 2 (Carolina Power & Light)
13. Sequoyah-2 (TVA)
14. McGuire (Duke Power)

ACSL MODULE	1	2	3	4	5	6	7	8	9	10	11	12	13	14
CONDEN	X													
COOLER		X	X											
DEAER	X	X	X	X	X	X								
FLASH	X							X						X
PIPESC		X	X	X	X	X		X						
PIPESR		X	X	X	X	X		X						X
PIPEWC		X	X		X	X	X	X	X	X				
PIPEWR		X	X		X		X	X	X	X	X			X
PUMPHC					X									
PUMPMD		X	X	X	X	X	X	X		X	X		X	X
PUMPTD	X	X	X		X						X	X		
TURBLP/HP		X	X		X	X								
VALVEC		X	X	X		X					X			
VALVED	X	X	X	X	X									
VALVEI		X	X		X	X	X		X			X		

CONTROL MODULES - ACSL Version

APPLICATION		

Sequoyah-2 (TVA)
Lansing Smith-2 (Southern Company Services)
McGuire (Duke Power)
Wilton-1 (Middle South Services)
San Onofre-2 (Southern California Edison)
Arkansas Nuclear One-2 (Systems Control)
TMI (Babcock & Wilcox)
TMI (General Public Utilities)
Potomac River-3 (PEPCO)
Grand Gulf Nuclear-1 (Middle South Services)
Robinson-2 (Carolina Power & Light)
Fermi-2 (Detroit Edison)
Mystic 7 (Bechtel)
Mystic 7 (Babcock & Wilcox)

ACSL MODULE	
ACT	X X X X
ONOFF	X X X X
PICONT	X X X X X X X X X X X X X X

FOSSIL MODULES - ACSL Version

APPLICATIONS	Lansing Smith-2 (Southern Company Services)	Wilton-1 (Middle South Services)	Mystic 7 (Bechtel)	Potomac River-3 (PEPCO)
ACSL MODULE				
AIRHX				
ATTEMP	X	X	X	
DRUMFC	X		X	X
DRUMNC		X		
ECON	X	X	X	X
OTBLR				
PULV				
REGHX				
SPRHTR	X	X	X	X

NUCLEAR MODULES - ACSL Version

ACSL MODULE	Grand Gulf Nuclear-1 (Middle South Services)	TMI (Babcock & Wilcox)	TMI (General Public Utilities)	Robinson-2 (Carolina Power & Light)	San Onofre-2 (Southern California Edison)	Arkansas Nuclear One-2 (Systems Control)
MSRHT	X					
OTSGEM	X	X				
PRESZR/SURJNC	X	X		X		
RX3	X					
UTSGR			X	X	X	

APPLICATION

Sequoyah-2 (TVA)
Potomac River-3 (PEPCO)
Grand Gulf Nuclear-1 (Middle South Services)
Lansing Smith-2 (Southern Company Services)
McGuire (Duke Power)
Wilton-1 (Middle South Services)
Robinson-2 (Carolina Power & Light
San Onofre-2 (Southern California Edison)
Fermi-2 (Detroit Edison)
TMI (General Public Utilities)
Mystic-7 (Bechtel)
Mystic-7 (Babcock & Wilcox)
TMI (Babcock & Wilcox)
Arkansas Nuclear One-2
(Systems Control)

ACSL MODULE

	Seq	Pot	GG	LS	McG	Wil	Rob	SO	Fer	TMI	M-B	M-BW	TMI-BW	ANO
CONNC	X	X	X		X			X	X	X				
CONNI	X	X	X	X	X	X	X	X	X	X	X	X	X	X
DIV	X	X	X	X	X	X	X	X	X	X	X	X	X	X
JUNC	X	X	X	X	X	X	X	X	X	X	X	X	X	X

TWO-PHASE MODULES - EASY5 Version

EASY5 MODULE \ APPLICATION	Semiscale (Jaycor)	LOFT (Babcock & Wilcox)	Vogtle (Babcock & Wilcox)	TMI Overcooling (Jaycor)	TMI Small Break (Jaycor)	Oconee Steam Line Break (Boeing Computer Services)	H. B. Robinson (General Electric)	Yankee Steam Line Break (General Electric)	Four Pipe Natural Circulation	TMI Natural Circulation (Bechtel)
ME	X	X	X	X	X		X			X
NU		X	X	X		X				
OG			X	X	X					X
PC	X	X	X	X	X		X	X		X
PI	X	X	X	X	X	X	X	X	X	X
PR	X	X	X	X	X	X	X	X		X
RL	X	X	X	X	X		X	X		X
RU	X	X	X	X	X		X	X		X
SL	X	X	X	X	X		X	X		X
SR	X	X					X	X		
UT	X						X	X		

MODULAR MODELING SYSTEM

THEORY MANUAL

PART II

GENERAL THEORY

PART II

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LIST OF FIGURES

NOMENCLATURE

Variables

ρ density

t   time

$\mathcal{V}$ velocity with respect to a fixed reference

e   energy per unit mass

p   pressure

q'"   heat transfer rate unit volume per unit time

$\dot{W}$ work done by the fluid stream (shaft work per unit volume per unit time)

σ_{ss} viscous sheer stress

x   distance along flow path

v   specific volume

g   gravitational acceleration

g_c dimensional constant

θ angle between flow path and horizontal plane

$\hat{A}$ area vector

V   volume

M   mass

cv   control volume

w   flow across control volume surface

q   heat transfer rate

u   specific internal energy

U   total internal energy

h   specific enthalpy

H   total enthalpy

G   bulk fluid momentum

F_w wall sheer stress function

α_h partial property of density with respect to enthalpy at constant pressure

α_p partial property of density with respect to pressure at constant enthalpy

α void fraction

T   temperature

ΔH head loss

f   pipe friction factor

L   length

D   diameter

K_1 pipe constant

C   flow conductance

C_0 two-phase distribution coefficient

q_r radiant heat transfer rate

U_r radiant heat transfer coefficient

U_c convective heat transfer coefficient

q_c convective heat transfer rate

U_{rc} equivalent convective heat transfer coefficient for radiant heat transfer

$\mathcal{V}_{gj}$ two-phase drift velocity

τ_d transport delay time

τ time constant

λ eigenvalues

$\mathcal{V}$ velocity

Subscripts

i,j   direction vector

s   surface

e   flow streams entering control volume

ℓ   flow streams leaving control volume

W   wall

H   Hot

m   Metal

Symbols

$\int_V$ volume integral

$\int_S$ surface integral

Section 1

GENERALIZED CONSERVATION EQUATIONS

1.1   BACKGROUND

The Modular Modeling System (MMS) includes many pretested component models called
modules. Components may be simulated using a variety of techniques determined by
the type of component, the phenomena of interest, and the application of the model.
Some components, such as an actuator, are simple mechanical devices. Simulation of
some components, such as valves and pumps, may require representation of experiment-
ally determined operating characteristics. Simulation of most power plant
components, however, is based on a rigorous application of the thermodynamic conser-
vation laws for mass, energy, and momentum and constitutive relations describing
heat transfer and fluid mechanics.

The general thermodynamic equations are developed by applying appropriate assump-
tions to the partial differential conservation equations to yield a solvable set of
ordinary differential equations. It is possible to derive the same set of ordinary
differential equations from a lumped parameter control volume analysis but some of
the inherent assumptions are obscured by this approach. All assumptions required to
arrive at the final equation sets are numbered consecutively and compiled at the end
of Section 3.

The objective of the MMS is to provide an economical and accurate analysis of the
dynamic interaction of several components within a process. It is not intended to
analyze the internal operation of any one component in detail. Consequently, it is
desirable to model only the significant component dynamics in as few nodes as
possible. The general equations developed below address one node in complete
detail. Where a specific module requires more than one node, the detailed extension
of the general equations is presented in the individual module derivation.

The MMS library of modules includes two types of modules which differ rather
radically in their formulation: "single-phase" modules and "two-phase" modules.
Single-phase modules are available to represent virtually all components in either

nuclear or fossil power plants. They are intended primarily for plant and control system design and analysis, and for evaluation of normal and abnormal transients which do not result from a violation of the system pressure boundary. Two-phase fluid is accounted for only in vessels or components where it exists under normal plant power conditions, e.g., steam drums, feedwater heaters, pressurizers, etc. Transitions from one phase to another, where they are treated, use simplifying assumptions. These modules are intended for economical simulation of long term transients.

Two-phase modules are available only for the NSSS primary loop components, duplicating the single-phase representations of these components. They are intended for safety analyses of the NSSS primary loop which may or may not result from a violation of the system pressure boundary. These modules use a Zuber-Findlay drift flux representation of two-phase flow and address level tracking, phase transition, and reverse flow rigorously.

The single-phase MMS formulations depend on the energy and the continuity equations to produce a solvable set of differential equations. The dynamic momentum equation is always considered optional, and is usually omitted - solving the steady-state momentum equation instead. The dynamic momentum equation dramatically shifts the system eigenvalues into the high frequency, underdamped, complex regime. Consequently, solution time for equation sets using momentum is much larger than without momentum. The momentum option is available in pipe modules, where momentum could be significant but is used in other modules only where necessary and at the discretion of the module developer. The general momentum equation is developed in the first three sections along with the continuity and energy equation so that the complete set of differential equations, when used, will be compatible.

The two-phase MMS formulations are based on the same fundamental continuity, energy, and momentum relations as the single-phase formulations. However, they also address the drift flux terms in these relations. Because the dynamic momentum equation is required to close the two-phase equation set, it is always carried (an option is available to reduce the response time and improve model economy where desired).

Finally, it is very important to recognize that the equations developed in the general portion of this manual describe only the majority of thermodynamic modules. The assumptions made during the development of the general equations are not imposed on all modules with the exception of those pertaining to module interconnections.

If it is desirable to represent kinetic energy changes, the appropriate terms can be added. Consequently, the general equations represent common treatment of MMS modules and reflect the judgment of the MMS developers as to the optimum trade-off between accuracy and computational costs.

1.2 THE LOCAL CONSERVATION EQUATIONS

The physical phenomena in thermal hydraulic systems are distributed along the flow path and vary with time. Consequently, the dynamics of the components are described by partial differential equations. The MMS modules are derived by discretizing the flow paths into finite length nodes thereby reducing the distributed effects to equivalent lumped parameters. The general local conservation equations are presented below with their associated assumptions. These partial differential equations are called local equations because they describe the dynamics at one point in the flow path. They must be integrated over the control volume to describe a complete node. The local equations can be derived several ways and are developed in many thermodynamic and fluid mechanics texts. (References 8-10.)

Conservation of Mass

$$\frac{\partial \rho}{\partial t} = - \frac{\partial(\rho \Psi_i)}{\partial x_i} \tag{1-1}$$

where

ρ = fluid density

Ψ = fluid velocity vector

i = direction vector subscript

Assumptions:

No mass is created or destroyed within the control volume. (A-1)

Conservation of Energy

$$\frac{\partial(\rho e)}{\partial t} = - \frac{\partial(\rho e \Psi_i)}{\partial x_i} - \frac{\partial(p \Psi_i)}{\partial x_i} + q''' - \dot{W} - \frac{\partial(\sigma_{ss} \Psi_i)}{\partial x_i} \tag{1-2}$$

where

e = energy per unit mass

= internal energy (u) + kinetic energy + potential energy

p = pressure

q''' = heat transferred per unit volume per unit time

$\dot{W}$ = work done by the system fluid (shaft work) per unit volume per unit time

σ_{ss} = viscous shear stress

Assumptions:

No energy is created or destroyed within the system. This in effect reduces to the same as A-1   (A-2)

Electrical and magnetic fields have negligible effect on the mass.   (A-3)

No chemical reactions occur within the volume   (A-4)

Conservation of Linear Momentum

$$\frac{\partial(\rho\Psi)}{\partial t} = -\frac{\partial(\rho\Psi_i\Psi_j)}{\partial x_i} - \frac{g_c\partial p_i}{\partial x_i} - \frac{g_c\partial\sigma_{ij}}{\partial x_i} - \rho g \sin\theta \qquad (1-3)$$

where

p = pressure

σ_{ij} = viscous shear force

g = gravitational acceleration

θ = angle between the direction of flow and the horizontal plane

Assumptions:

The volume is an inertial reference. That is, the volume being analyzed cannot be accelerating relative to a reference fixed in space, including rotational motion.   (A-5)

Magnetic and electrical fields have negligible contribution to the body forces.

Section 2

MMS NODE EQUATIONS - EXTENSIVE FORM

The preceding section presented the basic conservation laws. This section will apply the assumptions that are made for all MMS modules and arrive at a set of ordinary differential equations of the extensive properties. The ODE's for the intensive properties (per pound mass) require additional assumptions to relate the extensive properties to the intensive properties being calculated, and to treat the distributed heat transfer and transport delay phenomena. These equations are developed in later sections of the manual.

In converting the local equations to ordinary differential equations, frequent use is made of the Leibnitz rule for integrating over moving integration limits. This is required since the control volume boundaries may move with time. It is presented here and will be referred to in the following sections.

Leibnitz Rule:

$$\int_V \frac{\partial \phi}{\partial t} \, dV = \frac{d}{dt} \int_V \phi \, dV - \int_S \phi \vec{V}_s \cdot d\hat{A}$$

V = volume

$\vec{V}_s$ = surface velocity vector

ϕ = any extensive property (e.g., U,H,M) per unit volume

$\hat{A}$ = surface area vector (normal to surface and positive when outward from control volume (CV))

The left hand side (LHS) is the integral over a control volume (which may have moving boundaries) of a rate of change of an extensive property at a point. This is

the term in the conservation equations that must be converted to the right hand side (RHS) terms.

2.1 MMS NODE OR CONTROL VOLUME

Since the MMS allows each module to be formulated independently of other modules, there is no "typical" MMS node or control volume. However, a somewhat general node can be characterized as shown below in Figure 2-1 to exemplify the MMS modules and identify standard MMS limiting assumptions. Notice that the same volume (cell) is used for all three conservation laws. This differs from conventional treatment of partial differential equations (PDE) where the momentum cell is staggered from the energy and mass cell.
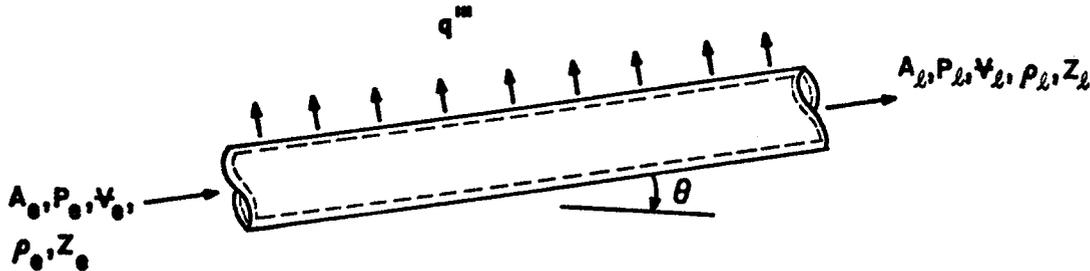
Figure 2-1. Generalized MMS Node

A = area ρ = density

p = pressure Z = elevation

$\mathcal{V}$ = velocity vector q''' = heat transfer per unit volume

The following assumptions apply to the general node above:

    No shaft work - modules providing shaft work are treated somewhat   (A-7)
              differently and are described individually.

    The velocity vectors are normal to the surface   (A-8)

    The flow within the control volume is one directional   (A-9)

    Viscous shear forces at the flow boundaries can be lumped with the   (A-10)
    frictional losses at the control volume walls

    Changes in potential and kinetic energy of the control volume are   (A-11)
    negligible

The inlet and outlet areas are constant with time   (A-12)

Heat conduction along the flow path is negligible   (A-13)

2.2 CONSERVATION OF MASS

To obtain the lumped parameter continuity equation, the local continuity equation (1-1) is integrated over the control volume:

$$\int_V \frac{\partial \rho}{\partial t} \, dV = - \int_V \frac{\partial(\rho \Psi_i)}{\partial x_i} \, dV \tag{2-1}$$

Applying the Leibnitz integration rule to the LHS yields

$$\frac{d}{dt} \int_V \rho \, dV - \int_S \rho \Psi_s \cdot d\hat{A} = - \int_V \frac{\partial(\rho \Psi_i)}{\partial x_i} \, dV \tag{2-2}$$

where

$d\hat{A}$ = an incremental area vector normal to the surface and positive when outward.

The RHS is the divergence term and can be converted to a surface integral using the divergence theorem as follows:

$$\int_V \frac{\partial(\rho \Psi_i)}{\partial x_i} \, dV = \int_S \rho \Psi_i \cdot d\hat{A} \tag{2-3}$$

Substituting 2-3 into 2-2 and transposing the surface integral on the LHS yields:

$$\frac{d}{dt} \int_V \rho \, dV = \int_S \rho \Psi_s \cdot d\hat{A} - \int_S \rho \Psi_i \cdot d\hat{A} \tag{2-4}$$

The integral on the LHS is the total instantaneous mass within the control volume. Therefore,

$$\frac{d}{dt} \int_V \rho \, dV = \frac{dM}{dt} \tag{2-5}$$

where

$\qquad$ M = instantaneous mass within the CV

Integrating the surface integrals around the control volume in Figure 2-1 provides the remaining terms.

$$\int_S \rho \Psi_s \cdot d\hat{A} = - A_e \rho_e \Psi_{se} + A_\ell \rho_\ell \Psi_{s\ell} \qquad (2\text{-}6)$$

where

$\qquad \Psi_{se}$ = velocity of CV boundary at entering surface
$\qquad \Psi_{s\ell}$ = velocity of CV boundary at leaving surface

$$\int_S \rho \Psi_i \cdot d\hat{A} = -A_e \rho_e \Psi_e + A_\ell \rho_\ell \Psi_\ell \qquad (2\text{-}7)$$

Substituting 2-5 through 2-7 into 2-4 and combining terms results in the extensive form of the continuity equation:

$$\frac{dM}{dt} = A_e \rho_e (\Psi_e - \Psi_{se}) - A_\ell \rho_\ell (\Psi_\ell - \Psi_{s\ell}) \qquad (2\text{-}8)$$

In control volume analyses, it is common to define a mass flux term as the flow across the control volume surface. Hence,

$$w = A\rho (\Psi - \Psi_s) \qquad (2\text{-}9)$$

Substituting this definition into 2-8 results in the well known lumped parameter continuity equation

$$\frac{dM}{dt} = w_e - w_\ell \qquad (2\text{-}10)$$

Note that the flowrates, w, are with respect to the surface while the velocities, Ψ, are with respect to a fixed reference.

2.3 CONSERVATION OF ENERGY

Integrating the local energy equation (1-2) over the control volume provides the following result.

$$\int_V \frac{\partial(\rho e)}{\partial t}\, dV = -\int_V \frac{\partial(\rho e\, V_i)}{\partial x_i}\, dV - \int_V \frac{\partial(p\, V_i)}{\partial x_i}\, dV + \int_V q'''\, dV - \int_V \dot{W}\, dV$$

$$-\int_V \frac{\partial \sigma_{ss}}{\partial x_i}\, V_i\, dV \qquad\qquad (2\text{-}11)$$

The LHS term is the storage; the first RHS term is the energy flux due to mass flow; the second, flow work, the third heat transfer; the fourth, shaft work exclusive of volume expansion; and the last work due to viscous shear stresses.

Each term in 2-11 will be considered separately starting from the LHS. Again the LHS is expanded using the Leibnitz formula.

$$\int_V \frac{\partial(\rho e)}{\partial t}\, dV = \frac{d}{dt} \int_V (\rho e)\, dV - \int_S \rho\, e\, V_s \cdot d\hat{A} \qquad\qquad (2\text{-}12)$$

Applying assumption A-1,

$$e = u \qquad\qquad (2\text{-}13)$$

Then recognizing the integral of the total derivative term in 2-12 is the total internal energy (U) in the CV,

$$\frac{d}{dt} \int_V (\rho u)\, dV = \frac{dU}{dt} \qquad\qquad (2\text{-}14)$$

Evaluating the surface integral in 2-12 for the control volume and applying 2-13 provides the energy flux term due to the moving boundary,

$$\int_S \rho e\, V_s \cdot d\hat{A} = - A_e \rho_e\, u_e\, V_{se} + A_\ell \rho_\ell\, u_\ell\, V_{s\ell} \qquad\qquad (2\text{-}15)$$

The first term on the RHS of 2-11 is the energy carried into the control volume via fluid flow. It is converted to a surface integral using the divergence theorem and then integrated over the control volume to give

$$\int_V \frac{\partial(\rho e \, V_i)}{\partial x_i} \, dV = - A_e \rho_e \, u_e \, V_e + A_\ell \rho_\ell \, u_\ell V_\ell \qquad (2-16)$$

Likewise the second divergence term, the flow work, becomes

$$\int_V \frac{\partial(p \, V_i)}{\partial x_i} \, dV = - A_e p_e V_e + A_\ell P_\ell V_\ell \qquad (2-17)$$

The heat flux term in 2-11 is a function of the temperature and heat transfer mode and will be addressed later. For development of the general node equtions, the heat transfer will be represented as

$$\int_V q''' \, dV = q \qquad (2-18)$$

The work term includes only shaft work not resulting from displacement of the control surface. With the conventions used for velocity, system expansion work is included in the flow work term.

$$\int_V \dot{W} \, dV = \dot{W}_s \qquad (2-19)$$

The viscous shear stress term accounts for work done by the system or on the system as a result of shear stresses due to displacement of the surface. This term is neglected in MMS. This should be distinguished from the effect on availability of these shear stresses which may be evaluated with a second law analysis.

$$\int_V \frac{\partial \sigma_{ss}}{\partial x_i} V_i \, dV = 0 \qquad (2-20)$$

Substituting 2-12 through 2-20 into 2-11, and combining like terms provides the extensive energy conservation equation.

$$\frac{dU}{dt} = A_e \rho_e \, u_e (\Psi_e - \Psi_{se}) - A_\ell \rho_\ell u_\ell \, (\Psi_\ell - \Psi_{s\ell}) + A_e p_e \Psi_e - A_\ell p_\ell \Psi_\ell + q - \dot{W}_s \qquad (2\text{-}21)$$

The energy equation is usually expressed in terms of flow across the boundaries. Using the previously defined definition of flow (2-9), the energy equation becomes

$$\frac{dU}{dt} = w_e(u_e + p_e v_e) - w_\ell \, (u_\ell + p_\ell v_\ell) + q - \dot{W}_s - p \frac{dV}{dt} \qquad (2\text{-}22a)$$

$$\frac{dU}{dt} = w_e h_e - w_\ell h_\ell + q - \dot{W}_s - p \frac{dV}{dt} \qquad (2\text{-}22b)$$

where
$$h = u + pv$$

2.4 CONSERVATION OF LINEAR MOMENTUM

The local momentum equation (1-3) must also be integrated over the control volume to develop the macroscopic momentum equation,

$$\int_V \frac{\partial}{\partial t} (\rho \Psi) \, dV = -\int_V \frac{\partial}{\partial x_i} (\rho \Psi_i \Psi_j) \, dV - g_c \int_V \frac{\partial p_i}{\partial x_i} \, dV - g_c \int_V \frac{\partial \sigma_{ij}}{\partial x_i} \, dV - \int_V \rho g \sin \theta \, dV \qquad (2\text{-}23)$$

As before each term will be expanded before substituting back into 2-23. Leibnitz rule is again applied to the LHS and integrated over the control volume to give

$$\int_V \frac{\partial}{\partial t} (\rho \Psi) \, dV = \frac{d}{dt} \int_V \rho \Psi \, dV - \int_s \rho \Psi_i \Psi_s \cdot d\hat{A} \qquad (2\text{-}24)$$

2-7

The total derivative term in 2-24 is the bulk momentum and will be defined as

$$\frac{d}{dt} \int_V \rho \mathcal{V} \, dV = \frac{d\,G}{dt}$$

(2-25)

The surface integral in 2-24 is integrated over the control volume to give

$$\int_S \rho \mathcal{V}_i \mathcal{V}_s \, d\hat{A} = -A_e \rho_e \mathcal{V}_e \mathcal{V}_{se} + A_\ell \rho_\ell \mathcal{V}_\ell \mathcal{V}_{s\ell}$$

(2-26)

The first divergence term on the RHS of 2-23 is the momentum flux. The next two divergence terms are the normal and shear forces respectively. These three terms are converted to surface integrals using the divergence theorem and then integrated over the control volume as follows:

For momentum flux,

$$\int_V \frac{\partial(\rho \mathcal{V}_i \mathcal{V}_j)}{\partial x_i} \, dV = \int_S \rho \mathcal{V}_i \mathcal{V}_j \cdot d\hat{A}$$

(2-27a)

$$= -A_e \rho_e \mathcal{V}_e^2 + A_\ell \rho_\ell \mathcal{V}_\ell^2$$

(2-27b)

For the normal forces,

$$g_c \int_V \frac{\partial p_i}{\partial x_i} \, dV = g_c \int_S p_i \cdot d\hat{A}$$

(2-28a)

$$= -g_c A_e p_e + g_c A_\ell p_\ell$$

(2-28b)

and for the viscous shear forces,

$$g_c \int_V \frac{\partial \sigma_{ij}}{\partial x_i} \, dV = g_c \int_S \sigma_{ij} \cdot d\hat{A}$$

(2-29)

The shear stress function is reduced to the frictional losses between the CV inlet and outlet. For development of the general equations, a wall shear force function, F_W, is used. Further discussion of this term is presented in Section 4. Therefore,

$$\int_S \sigma_{ij} \cdot d\hat{A} = - F_W \tag{2-30}$$

The last term in 2-23 is the volumetric body force or gravity head created when the flow vector has a vertical component. Since this force can only act in one direction, it is not a divergence term. Integrating it over the control volume results in

$$\int_V \rho g \sin \theta \, dV = A\rho g \, (z_e - z_\ell) \tag{2-31}$$

where

$\qquad$ A = representative average area

Now substituting equations 2-25, 26, 27, 28, 30, and 31 into 2-23 and combining like terms provides the macroscopic momentum equation:

$$\frac{dG}{dt} = A_e \rho_e \Psi_e (\Psi_e - \Psi_{se}) - A_\ell \rho_\ell \Psi_\ell (\Psi_\ell - \Psi_{s\ell}) + g_c \, (A_e P_e - A_\ell P_\ell - F_W)$$

$$+ A\rho g \, (z_e - z_\ell) \tag{2-32}$$

Converting the velocity terms to flow terms yields

$$\frac{dG}{dt} = w_e \Psi_e - w_\ell \Psi_\ell + g_c \, (A_e P_e - A_\ell P_\ell - F_W) + A\rho g \, (z_e - z_\ell) \tag{2-33}$$

Section 3

MMS NODE EQUATIONS - INTENSIVE FORM

3.1 INTENSIVE CONSERVATION EQUATIONS

The previous section resulted in a set of ordinary differential equations (ODE) for the extensive properties of mass, internal energy, and momentum. Although these equations are precise within the stated assumptions, they do not represent a closed or complete set and, therefore, cannot yet be solved. All three conservation equations require the properties of the fluid at the entering and leaving surfaces. In all cases, the entering fluid properties are assumed known either from boundary conditions or from the exiting properties of the upstream node. To complete the set of equations, the following relationships must be determined:

1. The relationship between the leaving surface intensive properties, ρ_ℓ (density) and u_ℓ (specific internal energy), the total stored mass and energy (U), and the entering surface intensive properties;

2. The relationship between the temperature distribution and the heat transferred (q in the energy equation); and

3. The relationship between pressure and flow to determine F_W in the momentum equation.

In all three cases, the difficulty arises because the properties involved are, in fact, distributed throughout the node but the equations require a single representative value. Additional assumptions must be made about the leaving property values to close the equation set.

It is important to recognize that there are no "good" choices among the possible assumptions for lumping parameters. Some modelers select one set of assumptions and others a different set. To argue the superiority of one set over another is a fruitless discuss of religions. The MMS does not impose any particular set of assumptions on the modeler as long as they result in equations compatible with those presented in this section. This manual is not intended to justify the assumptions employed in the MMS modules, but rather to identify the assumptions and their

impact, and describe the major factors considered in making the particular assumptions. The following discussion defines the major factors to consider and identifies the typical choices made in development of the modules described in Part III.

3.1.1 Defining Outlet Properties

As mentioned above, the conservation equations do not comprise a closed set of equations until a means of calculating the outlet properties is established. Thus far the conservation equations assume they are available but give us no equations to solve for them. It is also significant to note that the extensive properties that the conservation equations do calculate are seldom the variables of interest in a dynamic simulation. Most commonly the outlet intensive properties such as density and enthalpy are the variables of interest.

To convert the extensive conservation equations to a useful and solvable form requires an additional assumption about how the intensive properties are related to the extensive properties. Several choices are possible but each has its own problems. To present the alternatives and consequences, a simplified energy conservation equation will be used as an example.

For a control volume with no heat transfer through the surfaces, no work, and constant volume, the energy equation becomes

$$\frac{dU}{dt} = w_e h_e - w_\ell h_\ell \tag{3-1}$$

To further simplify this illustration, it will also be assumed that changes in flow work are negligible so that

$$\frac{dH}{dt} = w_e h_e - w_\ell h_\ell \tag{3-2}$$

It is now necessary to relate the outlet enthalpy (h_ℓ) to the entering enthalpy (h_e) and the total stored energy (H) to arrive at a solvable set of equations. A simple conversion can be achieved by defining an average enthalpy as

$$\bar{h} = \frac{H}{M} \tag{3-3}$$

where

    M = total mass from continuity equation.

Substituting 3-3 into 3-2, expanding the derivative, and solving for the internal energy derivative gives

$$\frac{d\bar{h}}{dt} = \frac{w_e h_e - w_\ell h_\ell - \bar{h}\frac{dM}{dt}}{M} \tag{3-4}$$

The value of the average enthalpy can now be defined by assuming an enthalpy profile across the CV from inlet to outlet. If a linear profile is assumed as shown in Figure 3-1, the definition of the average enthalpy becomes

$$\bar{h} = \frac{h_e + h_\ell}{2} \tag{3-5}$$

DISTANCE ALONG FLOWPATH
(FRACTION OF TOTAL LENGTH)
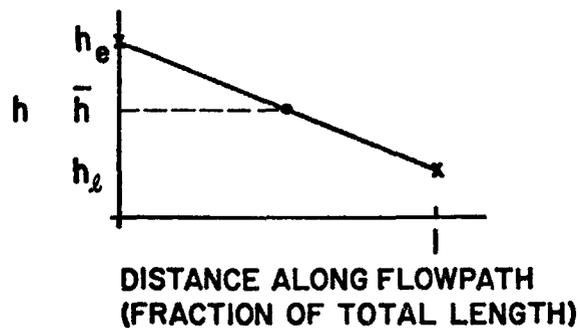
Figure 3-1. Linear Enthalpy Profile

Since $\bar{h}$ is always known because it is a state (output of an integrator), and h_e is always known from a boundary condition or upstream module, the outlet enthalpy is easily calculated and the energy equation can now be solved.

$$h_\ell = 2\bar{h} - h_e \tag{3-6}$$

This is a common and somewhat appealing assumption, but not without problems. Equation 3-4 generates the classical "see-saw" effect which is shown graphically in Figure 3-2.
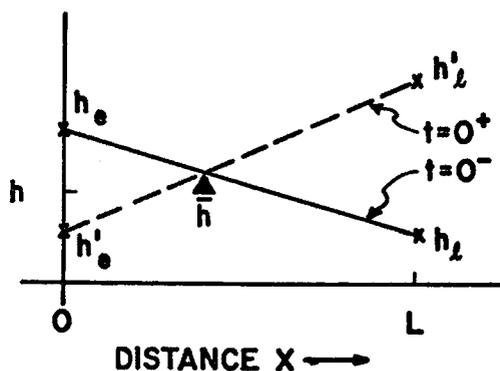
Figure 3-2. See-Saw Effect

Since $\bar{h}$ is a process state, it moves only by integrating the ODE (eqn 3-4). Hence, it moves with a time constant determined by the mass in the node. On the other hand, the entering enthalpy is free to move instantaneously. In actual processes, h_e can change in near step-wise fashion by suddenly opening or closing an upstream valve mixing fluids of different temperatures. Since the leaving enthalpy is calculated as an algebraic combination of $\bar{h}$ and h_e, it moves as quickly as h_e. As shown in Figure 3-2, the enthalpies, h_e, $\bar{h}$, and h_ℓ are shown at an equilibrium condition by the solid line. At time $t=0^+$ the entering enthalpy makes a step reduction to h_e'. Since the average enthalpy $\bar{h}$ is a state, it has not had time to move and, therefore, from the period $t=0^-$ to $t=0^+$ it remains fixed - hence it is depicted as the fulcrum of the see-saw. The leaving enthalpy, being calculated algebraically, "pivots" about $\bar{h}$ indicating a sudden increase in enthalpy at the outlet. Since the outlet enthalpy increase is non-physical, it is an undesirable response.

It is frequently argued that this see-saw effect is negligible because 1) the entering conditions do not make step changes, and 2) the effect is washed out when a large number of nodes are connected in series. These arguments are not entirely valid. First, the step increase at the inlet is the extreme case. The much more common case of a ramp change at the inlet will produce a see-saw effect if the ramp inlet is faster than twice the integration rate of $\bar{h}$. This can be seen by differentiating equation (3-6).

$$\frac{dh_\ell}{dt} = \frac{2d\bar{h}}{dt} - \frac{dh_e}{dt} \tag{3-7}$$

when

$$\frac{dh_e}{dt} > 2\frac{d\bar{h}}{dt} \tag{3-8}$$

then

$$\frac{dh_\ell}{dt} < 0 \tag{3-9}$$

and hence the non-physical see-saw effect is again visible.

Although the use of multiple nodes does alleviate the see-saw problem somewhat, it does not eliminate the problem, and it does increase the computational costs. The time constant of $\bar{h}$ is proportional to the mass in the node. By breaking a volume into n equal nodes, the mass per node is M/n. This reduces the time constant by a factor of n which increases the rate of change of $\bar{h}$ by n. As a result, the entering enthalpy, h_e, can change at a rate n times faster than it can for one node before see-saw effects are observable. In this sense, multiple nodes alleviate the see-saw effect.

In addition to the disconcerting appearance of a brief initial change in the wrong direction during simulation, see-saw has a more serious impact on the linear analysis results in the MMS. Much useful information can be gained from a process model inexpensively by special analysis routines such as eigenvalues, transfer functions, and root loci. These analyses are useful in designing control systems as

well as in analysis of process dynamic behavior. When the see-saw effect is even possible due to the definition of $\bar{h}$, an artificial pole (negative lead-type respone as opposed to lag) is created in the mathematics. If this erroneous information is used in the control design, the control system will respond incorrectly to certain disturbances.

Unfortunately see-saw exists anytime the following two conditions exist:

1. The state of the node is an intensive property and is defined as the value of the property anywhere other than the outlet, and

2. The value of the intensive property at the outlets is extrapolated from the inlet properties and the state.

To avoid see-saw, one alternative is to assume a flat profile as shown in Figure 3-3.
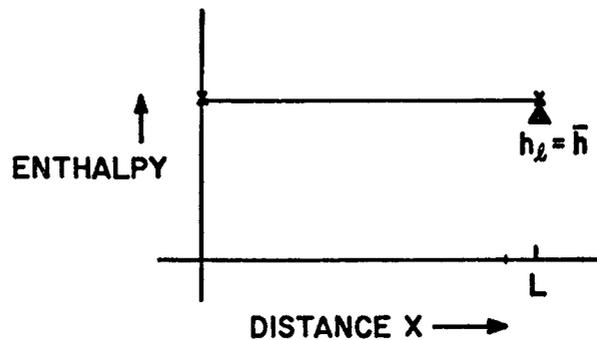
Figure 3-3. Flat Profile

This is referred to as the "stirred tank" approximation because a well stirred tank has the same temperature everywhere. Therefore, the leaving enthalpy is also the average enthalpy regardless of what the entering enthalpy is. For this assumption, the energy equation becomes

$$\frac{dh_\ell}{dt} = \frac{w_e h_e - w_\ell h_\ell - h_\ell \left(\frac{dM}{dt}\right)}{M} \qquad (3\text{-}10a)$$

$$= \frac{w_e h_e - w_\ell h_\ell - h_\ell (w_e - w_\ell)}{M} \tag{3-10b}$$

$$= \frac{w_e (h_e - h_\ell)}{M} \tag{3-10c}$$

Assuming a flat profile eliminates see-saw and its associated analytical problems, but is not without problems. This form of the energy equation is directly derivable only for the well stirred tank node. Since most dynamic problems involve tube type heat exchangers rather than well stirred tanks, equation 3-10 is conceptually unsatisfying since tube type heat exchangers clearly have a non-flat enthalpy profile.

A another alternative is to assume that the enthalpy derivative at the outlet is approximately equal to the derivative of the average. Hence

$$\frac{dh_\ell}{dt} = \frac{\overline{dh}}{dt} \tag{3-11}$$

This restricts only the derivative and does not require the average and outlet enthalpies to be equal. In other words, a non-flat enthalpy profile can still be considered without causing see-saw problems. The errors caused by the inconsistency between the definition of the state and its derivative are very small and only slightly affect the transients. All the alternative formulations above will converge to the correct steady state solution if parameterized correctly. However, the non-flat temperature profile allows a much more accurate calculation of heat transfer than stirred tank profile. This more than offsets the compromise on the transient slope. Comparisons with field data support the reasonableness of this assumption. Hence, for the MMS, the following additional assumption is made for most nodes:

> The derivative of the property leaving the node is   (A-14)
> approximately equal to the derivative of the average
> property.

With this additional assumption, a compatible set of intensive conservation equations can be developed.

3.1.2 The Intensive Continuity Equation

To develop the intensive continuity equation, the average density is defined as

$$\bar{\rho} = \frac{M}{V} \tag{3-12}$$

Substituting into the extensive continuity equation (2-10), expanding the derivative and solving for the derivative of ρ yields

$$\frac{d\bar{\rho}}{dt} = \frac{w_e - w_\ell - \bar{\rho}\left(\frac{dV}{dt}\right)}{V} \tag{3-13}$$

where

$$\frac{dV}{dt} = \text{rate of change of the control volume}$$
$$\text{(for moving boundary nodes)}$$

Applying assumption A-14 to prevent see-saw effects occurring on density changes results in the following MMS continuity equation.

$$\frac{d\rho_\ell}{dt} = \frac{1}{V}\left[w_e - w_\ell - \bar{\rho}\frac{dV}{dt}\right] \tag{3-14}$$

Notice that $\bar{\rho}$ on the RHS is determined by the profile assumption about a specific node. For example, for a stirred tank having a flat profile, $\bar{\rho} = \rho_\ell$. For a linear profile, $\bar{\rho} = \frac{1}{2}(\rho_e - \rho_\ell)$. In both cases, however, see-saw effects are avoided because the ˉstate (integrated value) is the outlet quantity.

3.1.3 The Intensive Energy Equation

The average internal energy is defined as

$$\bar{u} = \frac{U}{M} = \frac{U}{\bar{\rho}V} \tag{3-15}$$

Substituting into the extensive energy equation (2-22b), expanding the total derivative, and solving for the energy derivative yields

$$\frac{d\bar{u}}{dt} = \frac{1}{\bar{\rho}V}\left[w_e h_e - w_\ell h_\ell + q - \dot{W}_s - p\frac{dV}{dt} - \bar{u}\,\bar{\rho}\,\frac{dV}{dt} - \bar{u}\,V\,\frac{d\bar{\rho}}{dt}\right] \qquad (3\text{-}16)$$

Applying Assumption A-14 to avoid see-saw effects results in the following MMS energy conservation equation:

$$\frac{du_\ell}{dt} = \frac{1}{\bar{\rho}V}\left[w_e h_e - w_\ell h_\ell + q - \dot{W}_s - p\frac{dV}{dt} - \bar{u}\,\bar{\rho}\,\frac{dV}{dt} - \bar{u}\,V\,\frac{d\rho_\ell}{dt}\right] \qquad (3\text{-}17)$$

Again notice that both $\bar{\rho}$ and $\bar{u}$ are determined by the profile that is assumed for the specific node.

3.1.4 The Intensive Momentum Equation

The bulk momentum can be defined in terms of an average velocity, $\bar{V}$, as

$$G = M\,\bar{V} \qquad (3\text{-}18)$$

Substituting equation 3-12 for the mass gives

$$G = \bar{\rho}\,V\,\bar{V} \qquad (3\text{-}19)$$

Assuming the control volume has either a constant flow across sectional area, or can be represented by an average area, the volume term can be represented as

$$V = AL \qquad (3\text{-}20)$$

Hence the momentum term becomes

$$G = \bar{\rho}\,AL\,\bar{V} \qquad (3\text{-}21)$$

Replacing the average velocity with an average mass flow using

$$\bar{w} = \bar{\rho}\,A\,\bar{V} \qquad (3\text{-}22)$$

the momentum term becomes

$$G = L \, \overline{w} \qquad (3\text{-}23)$$

Substituting 3-23 into the momentum conservation equation (2-33), applying assumption A-14, and solving for the flow derivative provides

$$\frac{d\overline{w}}{dt} = \frac{1}{L}\left[w_e V_e - w_\ell V_\ell + g_c \left(A_e P_e - A_\ell P_\ell - F_W \right) + A\overline{\rho}g \left(z_e - z_\ell \right) - \overline{w}\,\frac{dL}{dt} \right] \qquad (3\text{-}24)$$

For the mass and energy equations, the states (integrated variables) were assumed to be the leaving values to avoid the see-saw effects. Unfortunately, if the average flow in the momentum equation is also assumed to be the leaving flow, the outlet flow conditions will be overspecified. Since both density and specific energy are calculated, and hence known, at the outlet, the pressure is also known from steam/water properties. If the momentum equation were used to solve for the outlet flow, then both pressure and flow would be calculated at the same port. This would require the user to provide boundary conditions of both pressure and flow at the same point, which is totally unrealistic. Since the density and energy terms cannot be changed without introducing see-saw effects, the momentum equation must be formulated to eliminate the problem. The assumption that the average flow is the mean flow between inlet and outlet will generate see-saw effects when flow changes are created but will propagate upstream instead of downstream.

> Hence, the only remaining choice is to assume the change $\qquad$ (A-16)
> in average flow is equal to the change in entering flow.

With this assumption, the MMS momentum conservation equation becomes

$$\frac{dw_e}{dt} = \frac{1}{L}\left[w_e V_e - w_\ell V_\ell + g_c \left(A_e P_e - A_\ell P_\ell - F_W \right) + A\overline{\rho}g \left(z_e - z_\ell \right) - \overline{w}\,\frac{dL}{dt} \right] \qquad (3\text{-}25)$$

Again, the average flow w can be tailored to the profile of the specific node.

3.1.5   Constitutive Equations

With the intensive conservation equations described in the previous sections, the following property functions will provide a closed set of solvable equations.

$$p = f(u, \rho) \tag{3-26}$$
$$T = g(u, \rho) \tag{3-27}$$
$$h \equiv u + p/\rho \tag{3-28}$$

The temperature function is required for evaluation of the heat transfer term, q, discussed later.

It should be noted here that when the momentum effects are considered negligible, the momentum equation is replaced by the steady state momentum equation. This requires no additional changes to the conservation equations and still provides a directly solvable closed set of equations. Section 4 discusses the steady state momentum equations.

3.2   MMS EQUATION SETS

Section 3.1 developed the intensive conservation equation from the extensive equations by making the three additional assumptions that the rates of change of the leaving properties ρ_ℓ, u_ℓ, and w_ℓ were approximately equal to the rates of change of the average values. This provided a means of closing the equation sets without undesirable see-saw. The resultant intensive properties calculated as system states are internal energy, u, and density ρ. Since these are the properties conserved by the fundamental conservation laws, they constitute the basic causal relationships.

In many circumstances, however, it is more desirable to use enthalpy, h, and pressure, p, as the system states. The following brief list cites a few reasons:

1.   Using density as a state creates numerical stability problems for implicit integration methods in the subcooled water regime.

2.   Initial conditions of pressure are frequently known and can provide an easier initialization task than with u and ρ.

3.   Values of u and ρ are not always needed and depending upon the component physics, some property evaluations can be eliminated.

The MMS allows use of either set of states, or even other sets such as u and p. Due to item 1 above, u and p are not recommended for subcooled water where low pressure drops (< 5 psi) occur across the module. The following section develops the h and p set of conservation and constitutive equations without any additional assumptions.

3.2.1 Conservation of Mass with States h and p

The density of a fluid can be uniquely determined by knowing the fluid enthalpy, h, and pressure, p.

$$\rho = f(h, p) \tag{3-29}$$

Taking the total time derivative of ρ gives

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial h}\bigg|_p \frac{dh}{dt} + \frac{\partial\rho}{\partial p}\bigg|_h \frac{dp}{dt} \tag{3-30}$$

The partial properties are designated as

$$\alpha_h = \frac{\partial\rho}{\partial h}\bigg|_p \tag{3-31}$$

$$\alpha_p = \frac{\partial\rho}{\partial p}\bigg|_h \tag{3-32}$$

Substituting 3-31, 32 into 3-30 and solving for the pressure derivative,

$$\frac{dp}{dt} = \frac{1}{\alpha_p}\left[\frac{d\rho}{dt} - \alpha_h\frac{dh}{dt}\right] \tag{3-33}$$

The derivative of density can be replaced with the intensive continuity equation 3-14. Substituting into 3-33 the pressure derivative becomes

$$\frac{dp_\ell}{dt} = \frac{1}{\alpha_p}\left[\frac{1}{V}\left(w_e - w_\ell - \overline{\rho}\frac{dV}{dt}\right) - \alpha_h\frac{dh_\ell}{dt}\right] \tag{3-34}$$

Notice that this form includes the derivative of enthalpy term which must be evaluated from the energy equation.

3.2.2 Conservation of Energy with States h and p

The energy equation (2-22b) is converted from internal energy to specific enthalpy by using

$$U = M \bar{u}$$

$$= M (\bar{h} - p/\bar{\rho})$$

$$= \bar{\rho} V (\bar{h} - p/\bar{\rho})$$

$$= \bar{\rho} V \bar{h} - pV \qquad (3-35)$$

Substituting into 2-22b gives

$$\frac{d(\bar{\rho} V \bar{h} - pV)}{dt} = w_e h_e - w_\ell h_\ell + q - \dot{W}_s - p \frac{dV}{dt} \qquad (3-36)$$

Expanding the derivative and solving for the enthalpy derivative provides the energy equation in terms of enthalpy

$$\frac{d\bar{h}}{dt} = \frac{1}{\bar{\rho} V} \left[w_e h_e - w_\ell h_\ell + q - \dot{W}_s - \bar{\rho} \bar{h} \frac{dV}{dt} - \bar{h} V \frac{d\bar{\rho}}{dt} + V \frac{dp}{dt} \right] \qquad (3-37)$$

Applying assumption 14 to 3-37 gives the MMS energy eqution in terms of enthalpy at the outlet port.

$$\frac{dh_\ell}{dt} = \frac{1}{\bar{\rho} V} \left[w_e h_e - w_\ell h_\ell + q - \dot{W}_s - \bar{\rho} \bar{h} \frac{dV}{dt} - \bar{h} V \frac{dp_\ell}{dt} + V \frac{dp_\ell}{dt} \right] \qquad (3-38)$$

Equation 3-38 becomes the energy equation in h and p. Note that it requires dp_ℓ/dt as an input and, as noted earlier, the continuity equation (3-34) requires dh_ℓ/dt. Since the two equations are linear in dp/dt and dh/dt, they can be solved simultaneously to arrive at independent pressure and enthalpy derivatives.

The simultaneous solution of the above equations will not be discussed in the general theory because the details of solving the two simultaneous equations are dependent upon further assumptions in the component models. For example, for fixed volumes, where compressibility effects on the energy are negligible, where fluid enthalpy profile is considered well mixed, and where potential and kinetic energy changes are negligible, the energy equation reduces to

$$\frac{dh_\ell}{dt} = \frac{1}{V\bar{\rho}} \left[w_e \ (h_e - h_\ell) + q \right]$$

(3-39)

This is a reasonable and commonly used set of additional assumptions for many MMS modules. Equation 3-39 is independent from dp/dt and the two equations need not be solved simultaneously.

3.2.3   Constitutive Equations for States h and p

The constitutive equations when using enthalpy and pressure for states require partial properties as well as temperature and density properties. Hence, to complete this equation set the following properties are required.

$$\alpha_h = \left. \frac{\partial \rho}{\partial h} \right|_p = f_1(h, \ p)$$

$$\alpha_p = \left. \frac{\partial \rho}{\partial p} \right|_h = f_2(h, \ p)$$

$$T = f_3(h, \ p)$$

$$\rho = f_4(h, \ p)$$

3.2.4   Summary of Assumptions

The following list is a compilation of assumptions made in the development of the general MMS node equations. Additional assumptions may be applied when developing specific module equations and will be cited separately under the module formula-

3-14

tions. The assumptions compiled below, however, apply to all MMS modules and will not be repeated in the specific module formulations.

A-1 No mass is created or destroyed within the control volume (node).

A-2 No energy is created or destroyed within the node.

A-3 Electrical and magnetic fields have negligible effect on the mass.

A-4 No significant chemical reactions occur within the node.

A-5 The control volume is an inertial reference. That is, the volume being analyzed cannot be accelerating relative to a reference fixed in space - including rotational motion.

A-6 Magnetic and electrical fields have negligible contributions to the body forces.

A-7 No shaft work within the node. Modules with shaft work are treated separately (e.g., pump).

A-8 Velocity vectors are normal to the surface.

A-9 The flow across the control volume surface is one directional. (This assumption is not made in the two-phase modules.)

A-10 Viscous shear forces at the flow boundaries can be lumped with the frictional flow losses at the control volume walls.

A-11 Changes in potential and kinetic energy of the control volume are negligible.

A-12 The inlet and outlet areas are constant with time.

A-13 Heat conduction along the flow path is negligible.

A-14 The rate of change of the property leaving the node is approximately equal to the rate of change of the average property.

A-15 The control volume has a constant flow cross sectional area or an average cross sectional area can be used without affecting the dynamics.

A-16 The rate of change of the entering flow is approximately equal to the rate of change of the average flow.

3.3 MMS TWO PHASE EQUATION SETS

This section presents the fundamental concepts and equations used in the development of the MMS Two Phase Component Library. Two-phase flow obeys all of the basic laws of fluid mechanics. The equations are merely more complicated or more numerous than those for single-phase flow.

The general capabilities and characteristics of the Two-Phase Library can be summarized as follows:

1. Can be applied to single-phase liquid or vapor flows as well as two-phase flows.

2. Uses drift-flux concepts to analytically model one dimensional two-phase flows.

3. Applicable to normal and/or reverse flow phenomena.

4. Includes treatment of level tracking, counter-current flow and flooding.

5. Can be used with the single-phase modules through the use of interface modules.

3.3.1 Drift-Flux Concepts

A variety of analytical models may be used to model two-phase flow. In the homogeneous model the fluid system is treated as a fluid with average properties and without a detailed description of the flow pattern.

In the separated-flow model, the phases are assumed to flow side by side. Separate equations are written for each phase and the interaction between phases is considered.

The Zuber-Findlay drift-flux model is essentially a separate-flow model in which attention is focused on the relative motion of the phases, rather than on the motion of the individual phases. Using the drift-flux model and the assumption of interfacial equilibrium between the steam and liquid phases, the separate phase equations may be combined into a single set.

Some of the terms associated with drift-flux concepts and general two-phase analysis are presented below:

1. α – void fraction; the volumetric fraction of steam in a two-phase system

$$\alpha = \frac{V_g}{V_g + V_f} \qquad (3\text{-}40)$$

2. X - quality or flow quality; the fraction of the total two-phase mass flow across a given area which is composed of steam

$$X = \frac{w_g}{w_g + w_f} \qquad (3\text{-}41)$$

3. J_i - superficial velocity; the volumetric flux or volumetric flow rate per unit area (units of velocity) of the ith component (J_g for the steam phase and J_f for the liquid phase)

$$J_g = \frac{Q_g}{A} \qquad (3\text{-}42)$$

$$J_f = \frac{Q_f}{A} \qquad (3\text{-}43)$$

$$J_g + J_f = J = \frac{Q}{A} \qquad (3\text{-}44)$$

where

    Q - the volumetric flow rate

4. V_{gj} - drift velocity; the difference between the steam component velocity and the average mixture velocity

$$V_{gj} = V_g - J \qquad (3\text{-}45)$$

$$V_g = \frac{J_g}{\alpha} \qquad (3\text{-}46)$$

$$V_f = \frac{J_f}{1 - \alpha} \qquad (3\text{-}47)$$

5. C_0 - distribution parameter; represents the ratio of the average of the product of flux and concentration to the product of the averages

$$C_0 = \frac{\overline{(\alpha\ J)}}{(\bar{\alpha})\ (\bar{J})}$$ (3-48)

where the bar denotes "average value"

3.3.2 Conservation of Mass with States h and p

The continuity equation 3-14 may be applied to a two-phase mixture,

$$\frac{d\rho_i}{dt} = \frac{1}{V_i}\ (w_1 - w_2)$$ (3-49)

where

   i - the ith two-phase node or volume

The density of a homogeneous two-phase fluid mixture can be uniquely determined by knowing the mixture enthalpy h_i and the pressure p_i.

$$\rho_i = f(h_i,\ p_i)$$ (3-50)

Taking the total time derivative of ρ_i gives

$$\frac{d\rho_i}{dt} = \frac{\partial \rho_i}{\partial h_i}\frac{dh_i}{dt} + \frac{\partial \rho_i}{\partial p_i}\frac{dp_i}{dt}$$ (3-51)

Combining 3-49 and 3-51, the equation for the conservation of mass becomes

$$\frac{\partial \rho_i}{\partial h_i}\frac{dh_i}{dt} + \frac{\partial \rho_i}{\partial p_i}\frac{dp_i}{dt} = \frac{1}{V_i}(w_1 - w_2)$$ (3-52)

Equation 3-52 is applicable for both normal flow direction (w > 0) and reverse flow direction (w < 0).

3.3.3 Conservation of Energy with States h and p

The energy equation 3-36 may be applied to two-phase systems with minor modifications:

$$\frac{d\left(\rho_i h_i - \frac{p_i}{J_c}\right)V}{dt} = \text{(flow of energy into volume by convection)}$$
$$- \text{(flow of energy out of volume by convection)}$$
$$+ \text{(heat added to volume)} + \text{(drift flux energy terms)} \quad (3\text{-}53)$$

Substituting 3-51 into the left hand side of 3-53 yields

$$\frac{d\left(\rho_i h_i - \frac{p_i}{J_c}\right)V}{dt} = \left[\left(\rho_i + h_i \frac{\partial \rho_i}{\partial h_i}\right)\dot{h}_i + \left(\frac{\partial \rho_i}{\partial p_i} h_i - \frac{1}{J_c}\right)\dot{p}_i\right]V \quad (3\text{-}54)$$

where

J_c - the Joule constant   778 ft-ℓbf/Btu

The right hand side of 3-53 must take into consideration the drift flux terms and the treatment of reverse flow. To better understand the treatment of reverse flow, consider the network illustrated in Figure 3-4.

NORMAL FLOW DIRECTION
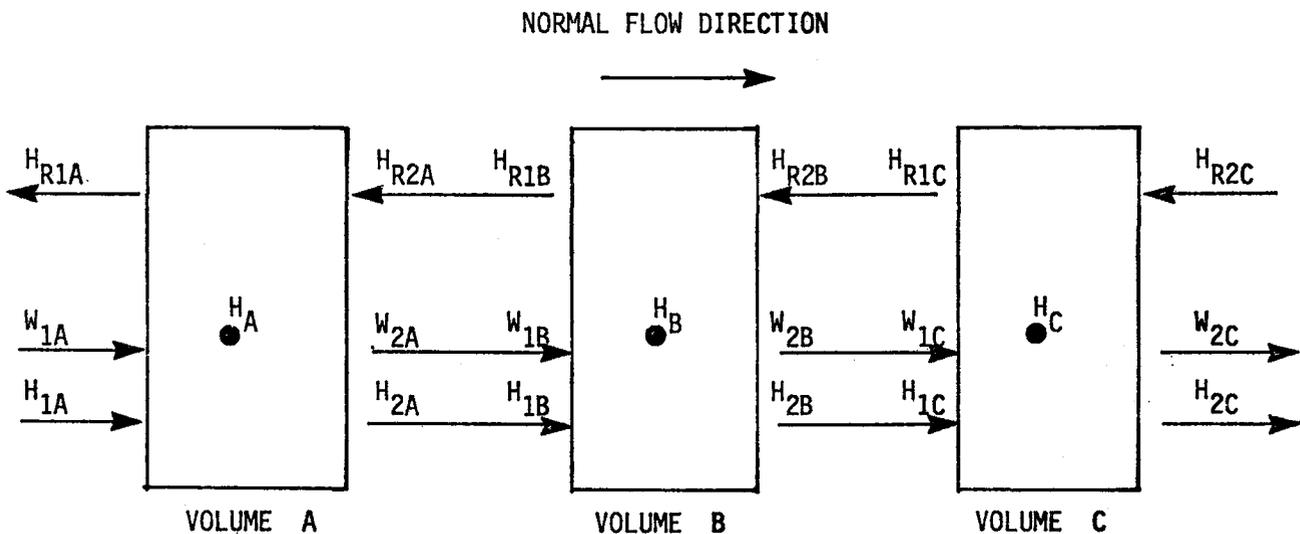
Figure 3-4. Reverse Flow Network

In Figure 3-4, quantities going into a volume are input quantities which are computed in an adjacent node and quantities leaving a volume are calculated in that volume. If volume A flows into B and B into C, then

$$
\begin{array}{ll}
W_{1B} = W_{2A} & W_{1C} = W_{2B} \\
H_{1B} = H_{2A} & H_{1C} = H_{2B} \\
H_{R2A} = H_{R1B} & H_{R2B} = H_{R1C}
\end{array}
\tag{3-55}
$$

$$
\begin{array}{lll}
H_{2A} = H_A & H_{2B} = H_B & H_{2C} = H_C \\
H_{R1A} = H_A & H_{R1B} = H_B & H_{R1C} = H_C
\end{array}
\tag{3-56}
$$

Consider volume B. H_B is the average enthalpy of the two-phase fluid in volume B and is a state variable. H_{2B} is the enthalpy of the fluid leaving volume B in the normal flow direction and H_{R1B} is the enthalpy of the fluid leaving volume B in the reverse flow direction. Both H_{2B} and H_{R1B} are always equal to H_B.

The right hand side of 3-53 may be written as

$$
RHS = [f_1 w_1 H_1 - f_2 w_2 H_2 + (1-f_1) w_1 H_2 - (1-f_2) w_2 H_{R2} + q]/V + \text{drift flux terms} \tag{3-57}
$$

$$
f_n = \begin{cases} 0 & w_n < 0 \\ 1 & w_n \geq 0 \end{cases}
$$

For flows in the normal direction ($w_1 > 0$, $w_2 > 0$), 3.57 reduces to

$$
RHS = (w_1 H_1 - w_2 H_2 + q)/V + \text{drift flux terms} \tag{3-58}
$$

which is similar to the RHS of 3-36 for single phase fluids.

For flows in the reverse direction ($w_1 < 0$, $w_2 < 0$) 3-57 reduces to

$$
RHS = (w_1 H_2 - w_2 H_{R2} + q) + \text{drift flux terms} \tag{3-59}
$$

Drift Flux Energy Terms

When the drift flux energy terms are considered, equation 3-57 becomes

$$RHS = [f_1 w_1 H_1 - f_2 w_2 H_2 + (1 - f_1) w_1 H_2 - (1 - f_2) w_2 H_{R2} - (1 - f_2) w_2 H_{R2} + q]/V$$
$$+ A [f_1 \Psi_1 z_1 - f_2 \Psi_2 z_2 + (1 - f_1) \Psi_1 z_2 - (1 - f_2) \Psi_2 z_R]/V \qquad (3\text{-}60)$$

where

$$H_n = h_n + \left(\frac{\alpha (C_0 - 1)}{\rho_f (1 - C_0) + \rho_i C_0}\right)_n \left(\frac{\rho_g \rho_f}{\rho_i} h_{fg}\right)_n \qquad (3\text{-}61)$$

$$z_n = \left(\frac{\alpha \rho_g \rho_f h_{fg}}{\rho_f (1 - C_0) + \rho_i C_0}\right)_n \qquad (3\text{-}62)$$

Ψ_n = drift velocity
A = cross sectional area

The complete energy equation is then obtained by combining 3-53, 3-54, and 3-60

$$\left(\rho_i + h_i \frac{\partial \rho_i}{\partial h_i}\right) \dot{h}_i + \left(\frac{\partial \rho_i}{\partial p_i} h_i - \frac{1}{J_c}\right) \dot{p}_i =$$

$$[f_1 w_1 H_1 - f_2 w_2 H_2 + (1 - f_1) w_1 H_2 - (q - f_2) w_2 H_{R2} + q]/V \qquad (3\text{-}63)$$

$$+ A [f_1 \Psi_1 z_1 - f_2 \Psi_2 z_2 + (1 - f_1) \Psi_1 z_2 - (1 - f_2) \Psi_2 z_R]/V$$

The mass equation 3-52 and 3-63 are a set of two simultaneous equations which must be solved to yield h_i and p_i. The solution gives:

$$\dot{p}_i = \frac{\left[\rho_i M_i - \frac{\partial \rho_i}{\partial h_i} E_i\right]}{D_i} \qquad (3\text{-}64)$$

$$\dot{h}_i = \frac{\left[\frac{M_i}{J_c} + \frac{\partial \rho_i}{\partial p_i} E_i\right]}{D_i} \qquad (3\text{-}65)$$

3-21

where

$$M_i = (w_1 - w_2)_i \tag{3-66}$$

$$E_i = f_1 w_1 (H_1 - H_2) + (1 - f_2) w_2 (H_2 - H_R) + q + A [f_1 \Psi_1 (z_1 - z_2)$$
$$+ (1 - f_2) \Psi_2 (z_2 - z_R) + z_2 (\Psi_1 - \Psi_2)] \tag{3-67}$$

In many applications where the drift flux energy terms are neglected, E_i is defined by:

$$E_i = f_1 w_1 (h_1 - h_2) + (1 - f_2) w_2 (h_2 - h_R) + q \tag{3-68}$$

$$D_i = V \frac{1}{J_c} \frac{\partial \rho_i}{\partial h_i} + \rho_i \frac{\partial \rho_i}{\partial p_i} \tag{3-69}$$

$$f_n = \begin{cases} 0, & w_n < 0 \\ 1, & w_n \geq 0 \end{cases}$$

3.3.4 Conservation of Linear Momentum

The general equation for the flow derivative in single phase flow is defined by equation 3-24. The corresponding equation for two-phase treatment will differ due to a consideration of reverse flow and drift flux terms.

$$\frac{dw_i}{dt} = \frac{A}{L} \left[g(p_{i-1} - p_i) - \rho_i \, gL \cos \theta - F_i |w_i| \frac{w_i \, L}{\rho_i \, A} \right]$$
$$+ \frac{(i+1-k)}{L} \left[\left(\frac{1}{\rho_{i-1}} - \frac{1}{\rho_i} \right) \frac{w_i^2}{A} + \frac{S_i}{\rho_{k-1} \, A} \left(w_{i-S_i}^2 - w_i^2 \right) \right] \tag{3-70}$$
$$+ \frac{A}{L} \left[\frac{\alpha_{i-1}}{1 - \alpha_{i-1}} \left(\frac{\rho_f \, \rho_g}{\rho} \right)_{i-1} - \frac{\alpha_i}{1 - \alpha_i} \left(\frac{\rho_f \, \rho_g}{\rho} \right)_i \right] \Psi_{gj}^2$$

where

$$k = \begin{cases} i \, , & w_i \geq 0 \\ i+1 \, , & w_i < 0 \end{cases}$$

$$S_i = \frac{|w_i|}{w_i}$$

F_i = flow resistance

In the two-phase components, the average flow w_i is assumed to be the exit flow. Thus equation 3-70 represents the flow derivative for the exit flow rate of a control volume.

An examination of 3-70 reveals that the coefficient of the momentum flux terms (i+1 - k) is equal to zero for negative values of w_i. This is done to eliminate the destabilizing effect of positive feedback during reverse flow due to the momentum flux terms.

3.3.5 Constitutive Equations for States h and p

For single phase flow conditions, the constitutive equations defined in Section 3.2.3 apply.

For two-phase homogeneous flow conditions, the following relations apply:

Mixture density

$$\rho_i = \frac{(\rho_f \, \rho_g \, h_{fg})_i}{\rho_g \, (h_g - h_i) + \rho_f \, (h_i - h_f)} \tag{3-71}$$

Void fraction

$$\alpha_i = \frac{\rho_i h_i - \rho_f h_f}{\rho_g h_g - \rho_f h_f} \tag{3-72}$$

Temperature

$$T_i = T_i(p_i)$$

$$\frac{\partial \rho_i}{\partial p_i} = f_1(h_i, \, p_i)$$

3-23

$$\frac{\partial \rho_i}{\partial h_i} = f_2(h_i, p_i)$$

where

$$\rho_f = \rho_f(p_i)$$
$$\rho_g = \rho_g(p_i)$$
$$h_f = h_f(p_i)$$
$$h_g = h_g(p_i)$$
$$h_{fg} = h_g - h_f$$

3.3.6 Two-Phase Level Tracking and Average Void Fraction

3.3.6.1 Two-Phase Level. The definition of a two-phase level is taken from analyses given by Sun, Duffey and Peng:

$$z_{mxt} = z_{kps} + \int_{z_{sat}}^{z_{mxt}} \alpha \, dz \tag{3-73}$$

where

z_{mxt} - height of the two-phase mixture

z_{kps} - "collapsed liquid height"

z_{sat} - level where the inlet water flow reaches saturation temperature

α - void fraction

Note that it is assumed that no subcooled boiling occurs.

If we define an average void fraction $\bar{\alpha}$ to be

$$\bar{\alpha} = \frac{1}{(z_{mxt} - z_{sat})} \int_{z_{sat}}^{z_{mxt}} \alpha \, dz \tag{3-74}$$

then equation 3-73 becomes

$$z_{mxt} = \frac{z_{kps} - \bar{\alpha} \, z_{sat}}{(1 - \bar{\alpha})} \tag{3-75}$$

The "collapsed liquid height", z_{kps}, is a fictitious height which represents the total liquid inventory in the region.

$$z_{kps} = \frac{M_f}{A \, \rho_f} \qquad (3\text{-}76)$$

where

M_f - fluid mass in the two-phase region

A - region cross-sectional area

ρ_f - liquid density

3.3.6.2 Average Void Fraction.
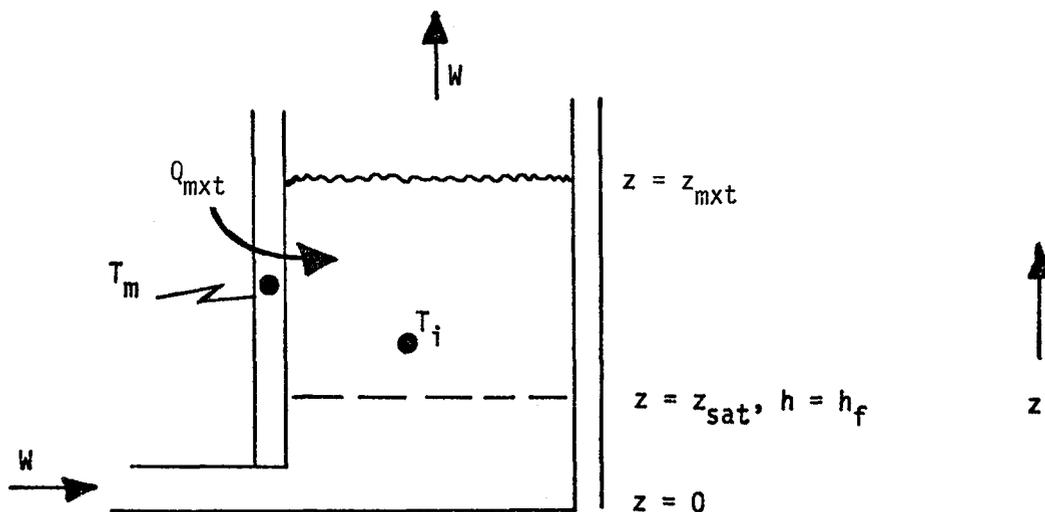
The average void fraction $\bar{\alpha}$ is defined in equation 3-74, where

$$\alpha(z) = \frac{J_g(z)}{C_0 \, (J_g + J_f) + V_{gj}} \qquad (3\text{-}77)$$

and

$$J_g(z) = \frac{Q_{mxt}(z)}{\rho_g \, A \, h_{fg}} \qquad (3\text{-}78)$$

Q_{mx} is the heat transferred from the vessel walls into the two-phase region. Over the length z_{mxt}, the wall temperature T_m and the fluid temperature T_i are considered constants.

$$\therefore\ Q_{mxt}(z) = U\ P\ (z - z_{sat})\ (T_m - T_i) \tag{3-79}$$

where

U = heat transfer coefficient

P = vessel perimeter

The liquid superficial velocity, J_f, can be eliminated from Eqn. 3-77 by the following consideration:

$$W = A\ (\rho_f J_f + \rho_g J_g)$$

$$\therefore\ J_f = \frac{W}{A\ \rho_f} - J_g\ \frac{\rho_g}{\rho_f}\quad,\ \text{and} \tag{3-80}$$

$$J_f + J_g = \frac{W}{A\rho_f} + J_g\ \left(1 - \frac{\rho_g}{\rho_f}\right)$$

Substituting equation 3-80 into 3-77 yields

$$\alpha(z) = \frac{J_g}{C_o\left[\dfrac{W}{A\ \rho_f} + J_g\ \left(1 - \dfrac{\rho_g}{\rho_f}\right)\right] + V_{gj}} \tag{3-81}$$

Substituting 3-78 and 3-79 into 3-81 yields

$$\alpha(z) = \frac{q\ z + Q_0}{C_o\left[\dfrac{W\rho_g\ h_{fg}}{\rho_f} + (q\ z + Q_0)\ \left(1 - \dfrac{\rho_g}{\rho_f}\right)\right] + \rho_g\ A\ h_{fg}\ V_{gj}} \tag{3-82}$$

$$q = U\ P\ (T_m - T_i)$$
$$Q_0 = -\ q\ z_{sat}$$

Equation 3-82 is of the form

$$\alpha(z) = \frac{A_1 + B_1 \, z}{A_2 + B_2 \, z} \tag{3-83}$$

where

$$A_1 = Q_0$$
$$B_1 = q$$

$$A_2 = C_0 \, w \, \gamma \, h_{fg} + C_0 \, Q_0 \, (1 - \gamma) + V_{gj} \, \rho_g \, A \, h_{fg}$$

$$B_2 = C_0 \, (1 - \gamma) \, q$$

$$\gamma = \frac{\rho_g}{\rho_f}$$

Equation 3-83 may be integrated to yield:

$$\int \alpha \, dz = \frac{B_1 \, z}{B_2} + \frac{(A_1 B_2 - A_2 B_1)}{B_2^2} \, \log \, (A_2 + B_2 \, z) \tag{3-84}$$

Subsitituting 3-84 into 3-74 yields:

$$\bar{\alpha} = \frac{B_1}{B_2} + \frac{(A_1 B_2 - A_2 B_1)}{B_2^2 \, (z_{mxt} - z_{sat})} \, \log \left(\frac{A_2 + B_2 \, z_{mxt}}{A_2 + B_2 \, z_{sat}} \right) \tag{3-85}$$

Section 4

MMS FLUID MECHANICS

This section addresses the assumptions and formulations used in most MMS modules to describe the pressure - flow relationships. In general, the flow is determined by the momentum equation. However, it is undesirable to use the dynamic momentum equation because it greatly increases computational costs without improving the results in most cases. As a result, the steady-state momentum equation is used to determine the pressure-flow relationships.

4.1 VISCOUS SHEAR LOSSES

Before the steady state momentum equation can be solved for flow, the viscous frictional losses, F_W, discussed in the previous section must be formulated. For incompressible flow in circular pipes, the head loss can be expressed as

$$\Delta H = \frac{fL}{D} \frac{V^2}{2g} \tag{4-1}$$

where

    H = head loss
    f = pipe friction factor
    L = pipe length
    D = pipe diameter
    V = nominal fluid velocity
    g = gravitational constant

The friction factor for a given pipe varies with Reynold's number and pipe roughness. However, for any given pipe roughness, the friction factor is constant for fully developed turbulent flow. Since the pipe roughness does not change during a transient period, and since the flow is turbulent even at 1% of design conditions, the friction factor over the transient period is assumed constant.

It is important to recognize that the MMS does not impose this requirement on any modules. If it is necessary to represent significant changes in friction factor due to, say laminar flow regimes, it can easily be incorporated into any module without affecting other modules. Applying the above assumption to equation 4-1, the head loss can be represented as

$$\Delta H = K_1 \frac{v^2}{2g} \qquad (4\text{-}2)$$

where

$$K_1 = \frac{f\ell}{D}$$

and K_1 is constant over a transient.

The head loss can be converted to pressure loss by multiplying by the fluid density, ρ, and correcting for units. When multiplied by the flow cross sectional area, it becomes the viscous force in the momentum equation.

$$F_W = A\rho K_1 \frac{v^2}{2g_c} \qquad (4\text{-}3)$$

The viscous loss can be put in terms of mass flow instead of fluid velocity.

$$F_W = \frac{K_1 w^2}{2A\rho g_c} \qquad (4\text{-}4)$$

4.2 THE STEADY-STATE MOMENTUM EQUATION

Substituting equation 4-4 into the momentum equation (3-25), and assuming the flow, w, and density, ρ, are taken at the entering port gives

$$\frac{dw_e}{dt} = \frac{1}{L}\left[g_c A(p_e - p_\ell) - \frac{K_1 w_e^2}{2 A\rho_e} + A \rho_e g(z_e - z_\ell) + \bar{w}\frac{dL}{dt}\right] \qquad (4\text{-}5)$$

This equation assumes a constant flow cross section throughout the node. For the quasi-steady state momentum equation, it is assumed the flow derivative is always

zero. Applying this assumption to a node with fixed surfaces and solving for the entering flow, w_e, gives

$$w_e = \sqrt{\frac{2g_cA^2}{K_1}\left[\rho_e(p_e - p_\ell) + \frac{g}{g_c}\rho_e^2(z_e - z_\ell)\right]} \qquad (4-6)$$

For control volumes with fixed cross sectional areas, MMS defines a flow conductance as

$$C = A\sqrt{2g_c/K_1} \qquad (4-7)$$

Substituting 4-7 into 4-6 gives the standard MMS steady state momentum equation.

$$w_e = C\sqrt{\rho_e(p_e - p_\ell) + \frac{g}{g_c}\rho_e^2(z_e - z_\ell)} \qquad (4-8)$$

4.3 COMPRESSIBLE FLOW

Many MMS components represent steam flow which in general is compressible. However, as noted in Reference 1, the pressure loss relationships for compressible fluid can be described with the same equations as incompressible flow if the pressure drop is small compared to the upstream pressure (less than 10%). Up until the pressure drop exceeds about 40% of the upstream pressure, the form of the flow equation remains the same, only the density changes from the upstream fluid density to an average density. As the pressure drop exceeds 40%, choking begins to occur and the pressure-flow relationship significantly changes since flow is no longer influenced by further decreases in downstream pressure.

Steam generating plant piping is designed to avoid choking conditions by a substantial margin. Other than low pressure relief lines and pipe breaks, choking does not occur. Consequently, the original MMS library does not provide the more complex and costly choked flow calculation in the pipes. Special pipes having this capability can easily be incorporated into the MMS library if required. Other components that can encounter choked conditions, such as compressible flow through valves, do include the choking capability in the MMS module. These are described individually in the module descriptions in Part III of this manual (e.g., see VALVEC).

Section 5

HEAT TRANSFER

One or more modes of heat transfer (radiation, conduction, convection) may occur in MMS modules. Conduction and convection are represented by the general heat transfer equation

$$q = U_0 \; A \; \Delta T \qquad\qquad\qquad (5\text{-}1)$$

where

U_0 = overall heat transfer coefficient

A = heat transfer surface area

ΔT = a representative heat transfer temperature difference

The following paragraphs describe the general MMS approach used in most modules. The reader is referred to individual module descriptions for details.

5.1 HEAT TRANSFER COEFFICIENTS

5.1.1 Radiant Heat Transfer

Heat transfer between two fluids through a heat exchanger is depicted in Figure 5-1.

The total heat transferred from the hot fluid to the metal is the convective plus the radiant heat. Conduction through the hot side fluid is always neglected. The radiant heat transfer, q_r, is calculated as a function of temperature to the fourth power

$$q_r = U_r \; A(T_H^4 - T_m^4) \qquad\qquad (5\text{-}2)$$

where

U_r is a radiant heat transfer coefficient

The total heat transferred from the hot fluid to the metal is then

$$q_1 = q_c + q_r \tag{5-3}$$
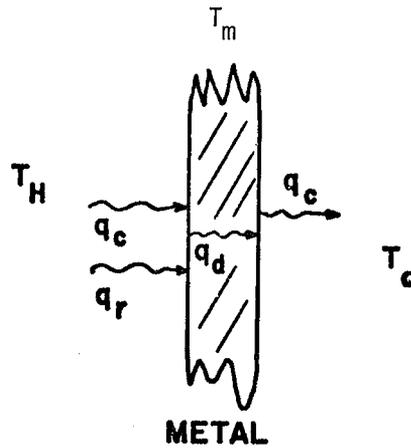
T_H = Temperature of hot fluid q_r = Radiant heat transfer
T_c = Temperature of cold fluid q_d = Conduction
q_c = Convective heat transfer T_m = Temperature of metal

Figure 5-1. Schematic of Heat Transfer in a Heat Exchanger

Radiant heat transfer is significant only on the hot side of tubes in fossil boilers because of the high gas temperatures and intertube radiation. Where radiation is accounted for, it is converted to an equivalent convective coefficient, U_{rc}, simply by

$$U_{rc} = \frac{q_r}{A \Delta T} \tag{5-4}$$

An equivalent heat transfer coefficient between the hot fluid and metal is defined as

$$U_{ec} = U_c + U_{rc} \tag{5-5}$$

and equation 5-3 becomes

$$q_1 = U_{ec} \, A \Delta T \tag{5-6}$$

Using an equivalent convective heat transfer coefficient for radiant heat transfer allows easier manipulation of the combined coefficient as will be discussed below, and provides a convenient indicator of radiant heat transfer effectiveness compared with convective heat transfer.

5.1.2 Convective Heat Transfer

Convective heat transfer coefficients in MMS modules are tailored to each individual module. Heat transfer correlations for the particular mode of heat transfer occurring provide the primary form of the equation for the coefficient. For example, in single phase, parallel or counter flow heat exchangers, the Dittus-Boelter correlation shown in 5-7 is commonly used as the basis for the coefficient.

$$h = 0.023 \frac{k}{D} Re^{0.8} Pr^{0.4} \qquad (5\text{-}7)$$

where

h = film coefficient
k = thermal conductivity of fluid
D = characteristic dimension
Re = Reynold's number
Pr = Prandtl number

To avoid confusing the film coefficient, h, with enthalpy, we will use U_c for the convective film coefficient in this part of the Theory Manual. By equation (5-7), the film coefficient is a function of several fluid properties: density, velocity, viscosity, and conductivity. However, the density and velocity are the predominant properties affecting the actual heat transfer. These properties can change more than the others during a transient or over a wide load range. Therefore, most MMS modules use the simplified form

$$U_c = K_c w^{.8} \qquad (5\text{-}8)$$

Where K_c is a multiplying factor that is determined from plant data or manufacturer's design data. In almost all cases this is a good approximation for a dynamic model since a dynamic model predicts changes from design conditions and is not used to calculate initial design conditions as a design code does. Furthermore, a

multiplying factor is required even when all properties are used to calibrate out the normal deviations in experimental data that produced the specific correlation. Pipe roughness, flow idiosyncrasies, and geometric factors cause deviations from the exact correlation predictions. Parameterizing the multiplying factor using plant data gives an exact fit to the actual plant at one point. If all the remaining factors are correctly accounted for, the correlation will be accurate over a very large range. Each module parameterization instruction includes detailed descriptions to calculate the multiplying factor.

The film coefficient discussed above characterizes the heat transfer for parallel or counter flow, single phase fluids. Other correlation forms are used for other conditions. Again it is important to recognize that the MMS does not require use of any particular correlation or any simplifying assumptions. Each module contains its own correlations tailored to the conditions it can encounter. However, most MMS modules use the same correlations for similar conditions. The simplified forms typically used in MMS modules are tabulated in Table 5-1. Note that all correlations have a multiplication factor to calibrate unknown effects against plant data. Only the dominant variables are explicitly used. The reader is referred to specific module descriptions for more details.

Table 5-1

TYPICAL MMS HEAT TRANSFER CORRELATIONS

Application	Design Formulation	Reference	Simulation Formulation
Fully developed Laminar Flow Inside Tubes	$U_c = c\left(\dfrac{K}{D}\right)$ (Neglecting Conduction Effects)	2	$U_c = K_c$ (Rarely occurs in power plant modeling)
Fully developed turbulent flow inside tubes	$U_c = 0.023\left(\dfrac{K}{D}\right)R_e^{0.8}\,P_r^{0.4}$	2 (Dittus-Boelter)	$U_c = K_c w^{0.8}$
Fully developed turbulent flow outside tubes e.g., flue gases	$U_c = 0.287\left\{\dfrac{G^{.61}C_p^{.33}K^{.67}}{D_o^{.39}\mu^{.28}}\right\}F_a$	3	$U_c = K_c w^{0.6}$
Radiant heat transfer in furnace	$q = .173F_b\left[(E_c+E_w)T_g\left(\dfrac{T_g}{100}\right)^4\right.$ $\left. - (E_c+E_w)T_b\left(\dfrac{T_b}{100}\right)^4\right]A$	4	$q = K_c\left[T_g^4 - T_b^4\right]$ T_g = gas temperature T_b = bulk wall temperature
Nucleate and bulk boiling	$T_w-T_{sat} = \dfrac{72\left(\dfrac{q''}{10^6}\right)^{\frac{1}{2}}}{\exp(P/1260)}$	2 (Thom)	$U_c = K_c\Delta T\,\exp(P/630)$

Table 5-1 (Cont.)

TYPICAL MMS HEAT TRANSFER CORRELATIONS

Application	Design Formulation	Reference	Simulation Formulation
Nucleate and bulk boiling	$U_c = 0.00122 \dfrac{k_\ell^{.79} c_\ell^{.45} \rho_\ell^{.49} g_c^{.25}}{\sigma^{.5} \mu_\ell^{.29} h_{fg}^{.24} \rho_u^{.24}}$ $\cdot \Delta T^{.24} \Delta p^{.75} s + h_{1p} f$ where $\Delta p = \dfrac{\Delta T\, h_{fg}}{T_{sat} U_{fg}}$ $h_{1p} = 0.023 \left(\dfrac{k_\ell}{d}\right)(1-x) R_e^{.8} P_r^{.4}$ s & f from tables	2 (Chen)	$U_c = \dfrac{K_{c1} \Delta T\, h_{fg}^{.5} S}{T_{sat}^{.5} \rho_v^{.24} U_{fg}^{.75}}$ $+ K_{c2}(1-x) w^{.8} F$ s & f obtained from tables
Film condensation on outside of horizontal tubes (e.g., feedwater heaters)	$U_c = \dfrac{1}{.06834(T)^{-.8912}}$	5	$U_c = K_c T^{-.9}$
Flat plate condensation (e.g., pressurizer walls)	---		$U_c = \dfrac{K_{c1} \Delta T}{K_{c2} + |\Delta T|} + K_{c3}$

5.1.3 Conductive Heat Transfer

Heat transfer by conduction is represented by the equation

$$q_d = U_d \, A \Delta T \qquad\qquad (5\text{-}10)$$

where
$U_d = k/\ell$
k = thermal conductivity
ℓ = wall thickness

The thermal conductivity, k, is obtained from manufacturers' data or handbook values for the specific material.

When the wall conductivity is very large compared to film coefficients, it is frequently neglected in MMS modules. This avoids unnecessary parameterization and computational costs. The conductivity can be relatively large for four reasons:

1. The film conductivity is very small (i.e., high film heat transfer resistance)

2. The material conductivity is very high (large k)

3. The wall thickness is very small

4. A significant tube fouling or slagging layer exists

5.1.4 Fouling and Slagging

Any heat exchanger that has been in operation for as little as one week may have a significant accumulation of deposits on the heat transfer surface. Unfortunately, these deposits may have a strong influence on the overall heat transfer coefficient but the fouling resistance is difficult to determine.

When fouling effects are accounted for, they are considered as another conduction layer on one or both sides of the heat exchanger tubes. The conduction heat transfer equation 5-10 is used where the conductance, U_d, is either estimated or backed out from plant data. Since fouling factors are sometimes available in units of resistance, this manual will refer to fouling resistance which is the inverse of conductance. The module parameterization instructions describe how to treat fouling for each module. For discussion purposes here, the fouling resistance will be

assumed known and will be referred to as R_f. Hence, the conduction equation for fouling becomes

$$q_d = \frac{A}{R_f} \Delta T \qquad (5\text{-}11)$$

5.1.5 Overall Heat Transfer Coefficient

In many modules, the energy stored in the heat exchanger metal is small compared to the energy stored in the fluid. In these cases, the metal mass need not be explicitly calculated as a state (integrated variable). In a large model this may provide a significant savings in computational cost since the computer costs increase with the number of states to a power greater than 1. This is also a good approximation since in most components the metal energy storage is less than 20% of the total.

When this approximation is applied, the heat transfer equation must be written in terms of the temperature differences between the two fluids and not in terms of the metal temperatures. Although metal temperatures can be approximated, they will only be algebraic combinations of the fluid temperatures when the metal temperature is not a state. In this case, the heat transfer coefficients are combined into one overally coefficient, U_o.

$$\frac{1}{U_o} = \frac{1}{U_{ec}} + R_{fh} + \frac{1}{U_d} + R_{fc} + \frac{1}{U_{cc}} \qquad (5\text{-}12)$$

where
$\quad U_{ec}$ = combined convective and radiant coefficient on the hot side
$\quad R_{fh}$ = fouling resistance on the hot side
$\quad U_d$ = conduction coefficient
$\quad R_{fc}$ = fouling resistance on the cold side
$\quad U_{cc}$ = convective coefficient on the cold side

The heat transfer is then calculated using the basic equation 5-1.

5.1.6 Multiple Heat Transfer Regions

It should be emphasized that the above discussion on heat transfer coefficients is applicable to a single node. When the types of heat transfer along the flow path change significantly, the form of the heat transfer coefficient must change. For

example, where boiling and superheating can occur within one component, each region (boiling region and superheating region) will require different forms for the convective coefficient. In components where two or more correlations are required each region within the component must be represented with a separate node. Moving boundary models can be used to represent nodes where the type of heat transfer changes constantly along the length of tube. This reduces the number of nodes necessary to achieve a reasonable approximation of heat transfer surface area.

5.2 HEAT TRANSFER SURFACE AREA

Where heat transfer surface area remains constant, the area term in equation 5-1 is lumped into the heat transfer coefficient, U_o. This is accomplished by calculating the calibration multiplier, K_c, on a module input/output basis. This cannot be done, however, in modules with moving boundaries or when the heat transfer surface area is a steam/water interface. In these modules, areas are either calculated directly (as in the once-through steam generator) or have compensation terms (as in the pressurizer sprays).

5.3 TEMPERATURE DIFFERENCE (ΔT) CALCULATIONS

The third term in the general heat transfer equation 5-1 is a representative temperature difference ΔT. The method used to calculate this term is very important to wide range accuracy because the ΔT is the heat transfer driving force, and it varies dramatically along the flow path. Figure 5-2 shows a typical temperature profile curve for a parallel flow heat exchanger. The ΔT is very large at the inlet and decreases along the flow path until typically it is very small at the outlet. For counterflow exchangers, Figure 5-3, the ΔT changes much less along the flow pat but it can increase or decrease along the path depending on flow conditions. For cross fow heat exchangers, any combination is possible.

The MMS design philosophy is to represent complete components in as few nodes as possible. For reasonable approximation to the heat transfer in a node over a wide range of operating conditions, one representative value of ΔT must be determined for the many conditions that can exist. To further complicate the calculation of ΔT, it is possible under dynamic conditions for the cold stream outlet temperature to be higher than the hot stream temperature. This must result in a negative heat flow or it will violate the second law of thermodynamics at steady state (see Figure 5-4). Therefore, the value of the driving force, ΔT must change signs when this condition occurs.
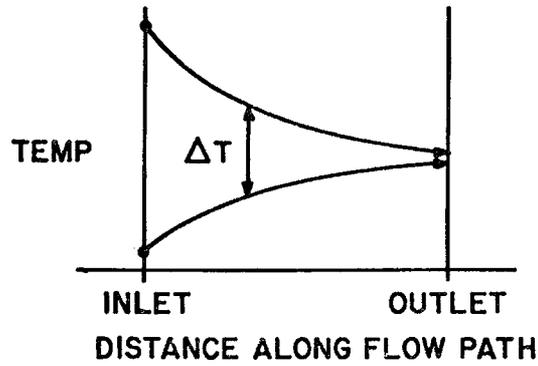
Figure 5-2. Typical Temperature Profile for Parallel
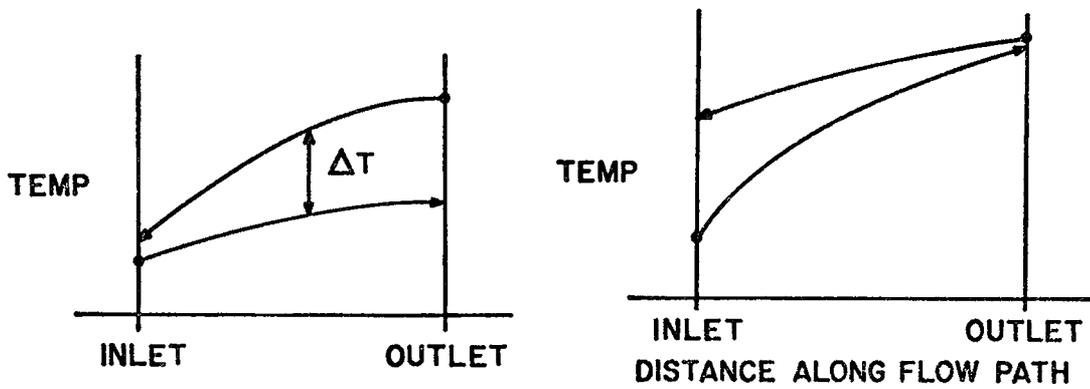Flow Heat Exchanger

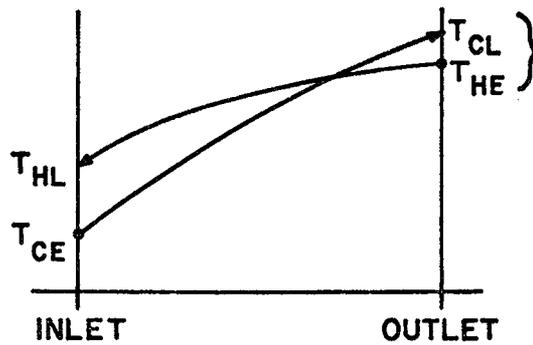Figure 5-3. Typical Temperature Profile for Counter Flow Heat Exchangers

Figure 5-4. Violation of Second Law of Thermodynamics

Several means of meeting the many requirements imposed on the ΔT calculation can be considered. A popular assumption is to use the difference between the average hot leg temperature and average cold leg temperature.

$$\Delta T = \frac{T_{HE} + T_{HL}}{2} - \frac{T_{CE} + T_{CL}}{2} \qquad (5\text{-}13)$$

However, this creates two errors. Referring again to Figure 5-4 it can be seen that the ΔT will be positive even when it results in a second law violation. Secondly, it is not an accurate correlation over a wide range of fluid inlet conditions.

Both of the above problems can be greatly alleviated by dividing the component into several nodes and then using the differences of averages (equation 5-13). With the smaller length nodes, the possibility of second law violations within the node is greatly reduced. If a violation does occur, the effect will be much smaller. In addition, the larger number of nodes provides a means of following the profile better and, hence, alleviates the wide range accuracy problem.

Unfortunately, using a large number of nodes increases the computational costs significantly because it increases the number of states. Consequently, the use of multiple nodes to represent one type of heat transfer is discouraged. It is recommended for MMS modules only when necessary, as in very long tubes.

Other methods of calculating ΔT have been evaluated for MMS applications. The best wide range general purpose method is believed to be the log mean temperature difference.

$$\Delta T = \frac{\Delta T_{max} - \Delta T_{min}}{\ln\left(\dfrac{\Delta T_{max}}{\Delta T_{min}}\right)} \qquad (5\text{-}14)$$

where

ΔT_{max} = larger of ΔT at inlet and ΔT at outlet
ΔT_{min} = smaller of ΔT at inlet and ΔT at outlet

When the log mean is formulated in terms of maximum and minimum temperature differences, it is valid for both parallel and counterflow exchangers. This method provides an accurate steady state solution for all possible entering fluid conditions without requiring multiple nodes. It does, however, require additional logic

to prevent a second law violation and avoid computational problems such as dividing by zero or finding the log of a negative number.

Despite the additional logic, the computational cost increase over other methods is small and is more than offset by the wide range accuracy of the log mean. Because of the complexity of the log mean algorithm, and the common use in many MMS modules, it has been installed in the library as a callable macro, LOGDT. The flowchart for LOGDT is shown in Figure 5-5.

ENTER

$|\Delta T_{MIN}| < \epsilon\ °F$ — Y → $\left|\left|\dfrac{\Delta T_{MAX}}{\epsilon}\right| - 1\right| < \epsilon/10^5$ — N → RECOMMEND $\epsilon = 3°$

N ↓ (from first diamond)

$\left|\left|\dfrac{\Delta T_{MAX}}{\Delta T_{MIN}}\right| - 1\right| < \epsilon/10^5$ — Y →

N ↓

PROVIDES SIGN

$$LMTD = \frac{\left(|\Delta T_{MAX}| - |\Delta T_{MIN}|\right)\dfrac{\Delta T_{MIN}}{|\Delta T_{MIN}|}}{\ln\left|\dfrac{\Delta T_{MAX}}{\Delta T_{MIN}}\right|}$$

NORMAL ROUTE

$$LMTD = \Delta T_{MAX}$$

$$LMTD = \frac{\left(\dfrac{\Delta T_{MIN}}{\epsilon}\right)\left(|\Delta T_{MAX}| - \epsilon\right)}{\ln\left|\dfrac{\Delta T_{MAX}}{\epsilon}\right|}$$

PROVIDES SMOOTH TRANSITION
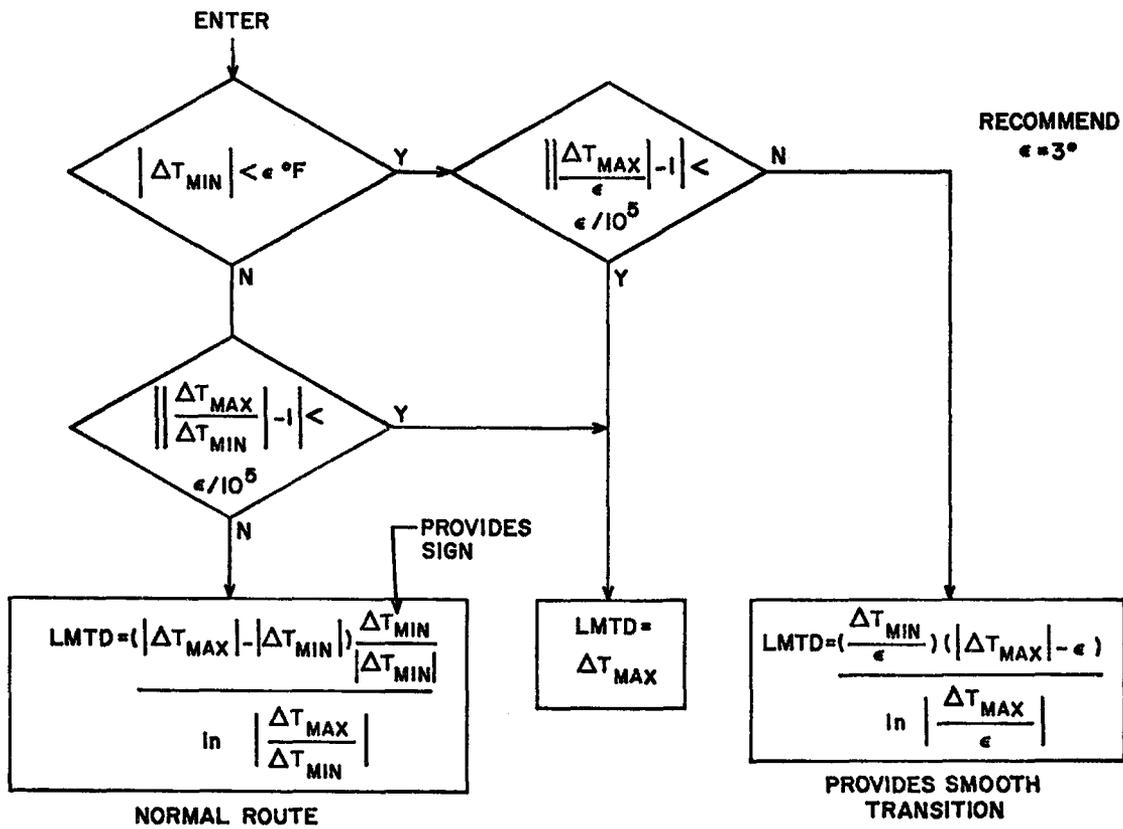
$$LMTD = \frac{\Delta T_{max} - \Delta T_{min}}{\ln\left(\dfrac{\Delta T_{max}}{\Delta T_{min}}\right)}$$

This form is valid for parallel or counter flow

	Counter Flow	Parallel Flow
ΔT_{max} = Max of	$\begin{cases} T_{HE} - T_{CL} \\ T_{HL} - T_{CE} \end{cases}$	$\begin{cases} T_{HE} - T_{CE} \\ T_{HL} - T_{CL} \end{cases}$
ΔT_{min} = Min of	$\begin{cases} T_{HE} - T_{CL} \\ T_{HL} - T_{CE} \end{cases}$	$\begin{cases} T_{HE} - T_{CE} \\ T_{HL} - T_{CL} \end{cases}$

Figure 5-5. LOGDT Calculation Logic

Section 6

TRANSPORT DELAY

Most steam generation processes contain long piping runs between major components. These long runs introduce transport delays of several seconds into the dynamics. Large heat exchangers, despite shorter flow paths, can introduce similar size transport delays because of their much lower fluid velocities. When the transients of interest are in the time span for the transport delay, it may be necessary to represent the transport phenomenon. The MMS provides two user selectable methods for modeling transport delays in piping runs: 1) variable size delay memory, and 2) multiple nodes. Although both methods will increase computational time and cost, the simple delay memory cannot be used if heat transfer to the walls or surroundings occurs. Consequently, the delay memory approach is recommended only when deemed essential and appropriate for a particular application. Transport delay within other components such as heat exchangers is not typically selectable. If deemed important by the component developer, the transport phenomenon is accounted for within the module at all times. Since this need usually occurs only for heat exchangers, the delay function is accounted for by choosing the appropriate number of nodes within a module.

The following two paragraphs describe the two methods used within MMS pipe modules to represent transport delay.

6.1 DELAY MEMORY

The delay memory method of representing transport delays stores the energy at the inlet of the module and assigns that energy level to the output value after the appropriate time delay. Since the internal energy is transported at the fluid velocity, while pressure transport is near instantaneous, only the internal energy, u, is delayed. Hence, the outlet internal energy is given by

$$u_\ell(t) = u_e (t - \tau_d) \tag{6-1}$$

where

τ_d = Time delay in seconds

The enthalpy leaving the module is then calculated as

$$h_\ell(t) = u_\ell(t) + p_\ell/\rho_\ell \qquad (6\text{-}2)$$

Where the leaving port pressure and density are either known boundary conditions, calculated from the continuity equation or calculated as a function of the other two properties.

This transport representation assumes no heat transfer occurs within the module, since the dynamic energy equation is not used. The time delay is calculated based on the leaving flow rates, w_ℓ, and the total mass within the control volume ($\rho_\ell V$):

$$\tau_d = \frac{\rho_\ell V}{w_\ell} \qquad (6\text{-}3)$$

The delay time varies continuously as w_ℓ and ρ_ℓ change and is properly accounted for in the module. For implementation details, refer to the ACSL or EASY manuals.

6.2 TRANSPORT DELAY VIA MULTIPLE NODES

The recommended method for representing transport delays is to divide the flow stream into multiple nodes and represent each node with a separate dynamic energy equation. A continuity equation may be written for each node separately or one continuity equation can be used for the entire module. As the number of nodes increases, the solution approaches a pure transport delay solution and the heat transfer is more accurately represented because the averaging over long tube lengths is reduced. This can be shown with the following simple frequency domain analysis.

The single node energy conservation equation for a water heat exchanger assuming only that the compression work (V dp/dt) is negligible, is

$$\rho_\ell V \frac{dh_\ell}{dt} = w_e(h_e - h_\ell) + q \qquad (6\text{-}4)$$

Converting to the frequency domain 6-4 becomes

$$\rho_\ell V \, Sh_\ell(S) = w_e(S)h_e(S) - w_e(S)h_\ell(S) + q(S) \qquad (6\text{-}5)$$

To examine transport delay phenomenan, we can look at the transfer function between the incoming enthalpy, h_e, and the leaving enthalpy, h_ℓ, assuming the other terms are momentarily constant. Hence

$$\frac{h_\ell(S)}{h_e(S)} = \frac{1}{\dfrac{\rho_\ell V}{w_e} S + 1} \qquad (6\text{-}6)$$

This shows that the outlet enthalpy will lag the inlet enthalpy with a time constant of $\tau = \rho_\ell V / w_e$ if the other terms remain constant.

If the heat exchanger is modeled as n equal nodes, the volume of each node, V_n, will be

$$V_n = V/n \qquad (6\text{-}7)$$

The flow and density in each node will be approximately equal, therefore, the time constant of each node, τ_n, is

$$\tau_n = \frac{\rho V}{w_e n} \qquad (6\text{-}8)$$

The transfer function for the entire heat exchanger is then represented by n nodes or

$$\frac{\Delta h_\ell(S)}{\Delta h_e(S)} = \left(\frac{1}{\dfrac{\rho_\ell V}{w_e n} S + 1} \right)^n \qquad (6\text{-}9)$$

Let

$$\tau = \frac{\rho_\ell V}{w_e} \qquad (6\text{-}10)$$

As the number of nodes increases, the transfer function approaches the limit:

$$\frac{\Delta h_\ell(S)}{\Delta h_e(S)} = \lim_{n \to \infty} \left[\frac{1}{\frac{\tau S}{n} + 1} \right]^n \tag{6-11a}$$

$$= \lim_{n \to \infty} \left[\frac{1}{\left(\frac{\tau S}{n} + 1\right)^n} \right] \tag{6-11b}$$

From the binomial expansion and the exponential series, the denominator of 6-11b can be represented as

$$\lim_{n \to \infty} \left(\frac{\tau S}{n} + 1 \right)^n = e^{\tau S} \tag{6-12}$$

Hence, the transfer function becomes

$$\frac{\Delta h_\ell(S)}{\Delta h_e(S)} = e^{-\tau S} \tag{6-13}$$

This is recognized as the Laplace transform of a pure transport delay.

In practice, n must be quite large ($\geq$ 20) before a pure delay is reasonably approximated for a step change at the inlet. Fortunately, however, step changes are rare (but not impossible) and dividing heat exchangers and long pipes into three or more nodes provides significant transport delay effects for most transients.

Section 7

NUMERICAL INTEGRATION

The application of the conservation equations to all the components in a model pro-
duces a large set of ordinary differential equations to be solved. These equations
are solved numerically with a method tailored to the characteristics of power plant
models. It is not the intent of this section to treat numerical methods in depth.
The reader is referred to reference 6 for an excellent and relevant discussion on
numerical methods. The following paragraphs describe the process model character-
istics that dictate the type of numerical method used and the general character-
istics of the MMS numerical integration method.

7.1 PROCESS MODEL CHARACTERISTICS

One of the primary objectives of the MMS is to greatly reduce the time and exper-
ience required to successfully generate a model. In solving the model equations, a
major decision is which numerical method to employ and what time step to use. This
decision is typically reached through time consuming experimentation with the model.
Since the characteristics of the MMS equations are known prior to model generation,
the numerical method can be tailored to the equations and the engineering time and
experimentation can be eliminated.

The most significant model characteristic that dictates the numerical method is the
range of eigenvalues. For discussion purposes, the eigenvalues can be thought of as
the inverse of the system time constants. Although a given system eigenvalue cannot
typically be identified with one particular equation, they tend to fall in identifi-
able groups. Figure 7-1 shows a typical range of eigenvalues for a power plant
model. Each shaded area indicates the type of equations in the same model. The
time constants associated with the continuity equations are much faster than those
associated with the thermodynamics, or energy equations. In fact, the continuity
equations typically create eigenvalues that are faster than the time frame of
interest. For example, during a turbine trip transient, information at 0.5 second
intervals is usually sufficient for the desired analyses. However, the time
constants associated with the continuity equations are .01 seconds and smaller.

Hence, with respect to the time frame of interest, the continuity equation "dynamics" are much faster. When the fastest model eigenvalue is much faster than the eigenvalues or time constants of interest, the model is called "stiff". The stiffness ratio is defined as the largest eigenvalue divided by the eigenvalue of interest. Stiffness ratios from 10^3 to 10^6 are not uncommon in power plant models. It is desired that the integrator take time steps no shorter than about

(MOMENTUM EQUATIONS)

BOILER TEMPERATURES

(ENERGY EQUATIONS)

STEAM & WATER FLUID MECHANICS

CONTROLS & FURNACE DRAFT

(CONTINUITY EQUATIONS)
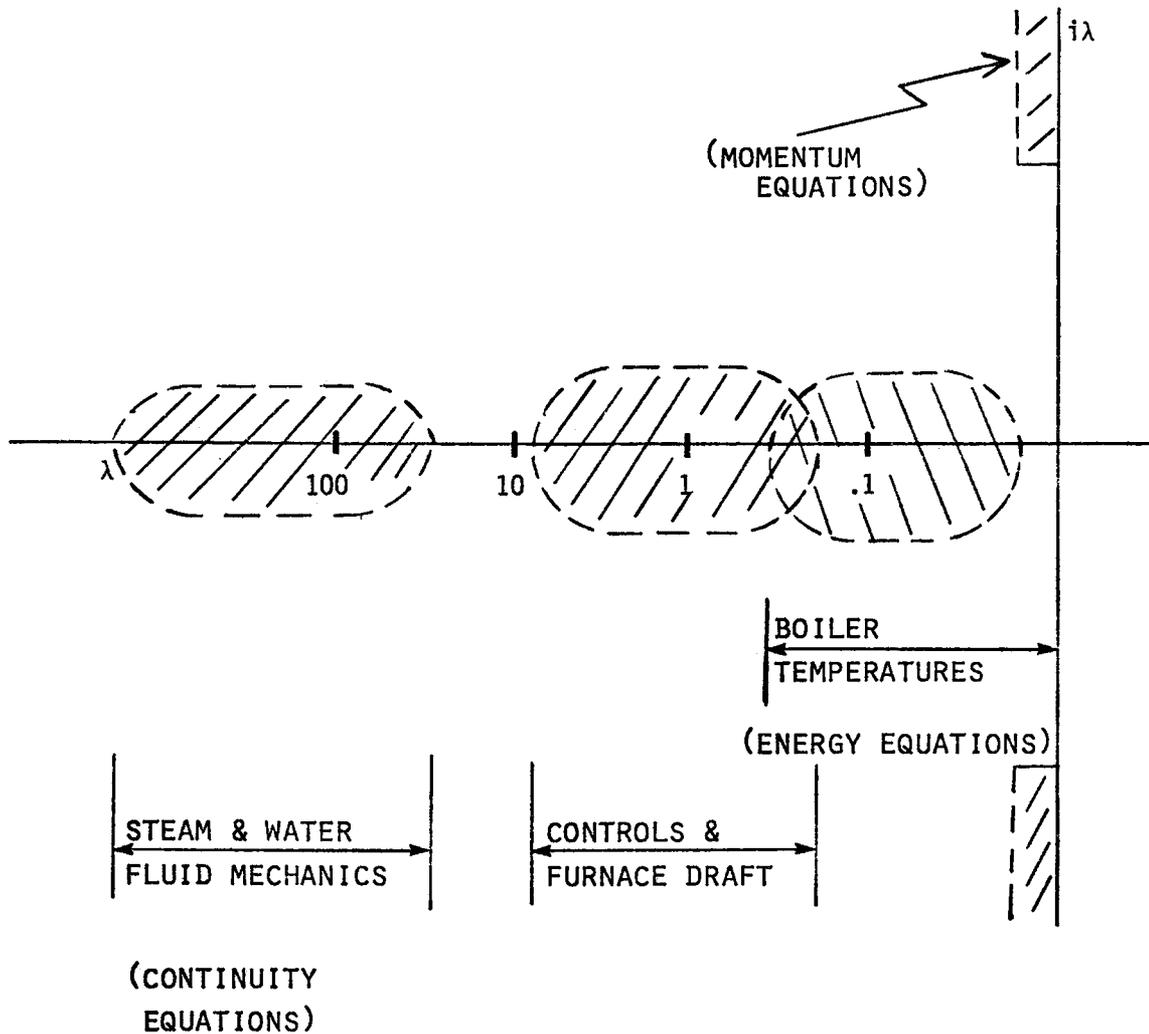
Figure 7-1. Typical Power Plant Eigenvalues

10% of the shortest time constant of interest, which may be a second or greater. With conventional explicit type integrators, however, the time step must be less than about 10% of the shortest model time constant to maintain stability. This can be a very small fraction of a second. Thus, a time step of .001 second would be required for a system of equations whose fastest time constant was .01 second.

This requires many passes through the computer model to reach the time period typically desired of several seconds or minutes.

The energy equations create eigenvalues in the .1 to 100 second time frame. Hence, it is typically the dynamics of the energy transfer throughout the process that are of primary interest. Unfortunately, the energy equations by themselves do not provide a closed set of state equations as discussed in Section 1 through 3 of this manual. The continuity equations are required to close the equation set. Furthermore, the dynamic continuity equations must be used to avoid implicit state equations and maintain modularity. That is, even though the dynamics of the continuity equations are quasi-steady-state with respect to the time frame of interest, they cannot be solved algebraically. They must be solved via ordinary differential equations which then introduce the undesirable stiffness discussed above.

Other methods exist for solving stiff model equations but most require either case by case judgments and a great deal of experience, or they compromise the desired modularity of the MMS. Consequently, the MMS uses integration methods that are tailored to models with this stiffness characteristic. These methods are referred to as "stiffly stable" methods and are discussed briefly in the following section.

7.2 STIFFLY STABLE INTEGRATION METHODS

Process models with stiffness ratios similar to power plant models occur in many industries. As a result, much attention by national laboratories, universities, and numerical methods experts has been directed toward improving solution methods. In 1971, Professor C. W. Gear published a book describing his concept of stiff stability and documenting the first complete software package for solving stiff models efficiently. Since that time many enhancements to the original algorithm have been made and work continues throughout the world to develop even more efficient stiffly stable integrators. It is the philosophy of the MMS to exploit these activities being performed outside the power industry. It is believed this approach will produce continual and significant improvements in the MMS at low costs and provide the best solution methods available.

The concept of stiff stability can best be described by looking at typical stability characteristics of integration algorithms on the real-imaginary plane. The shaded area of Figure 7-2 shows the stability region for a forward Euler integration method.
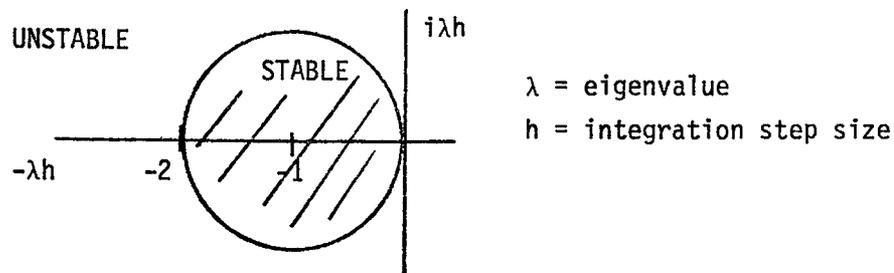
Figure 7-2. Stability Region of Euler Integrator

For any λh product outside the circle, the solution is guaranteed to be unstable.
Hence, if a model contains even one eigenvalue of, say, 100 (time constant of .01),
the step size must be no larger than .02 seconds to remain within the stable region.
Although this will be stable, it will give very poor results. Practically a step
size smaller than .002 must be used.

All explicit integration methods have a left side stability limit. That is, they
all have a value of λh which, if exceeded, will produce an unstable solution.
Generally speaking, stiff stability is the notion that all the eigenvalues in the
left half plane are stable regardless of step size. This is further extended to the
idea that the quasi-steady-state eigenvalues need not always have the same dynamic
accuracy as the smaller eigenvalues. This notion is characterized by the stability
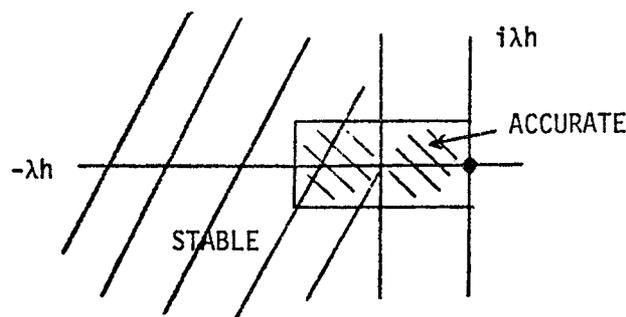diagram shown in Figure 7-3.

Figure 7-3. Stability Diagram

For a stiffly stable integration method, all eigenvalues to the left of a vertical
line on the real-imaginary plane are stable, while eigenvalues near the vertical

axis are more accurate than those farther away. With this characteristic, the large eigenvalues caused by the continuity equations can be integrated with a large step size without becoming unstable. The loss in dynamic accuracy for these is academic since they are quasi-steady-state relative to the energy equations. Hence, the total system of equations can be integrated more efficiently.

To achieve stiff-stability, an integration method must be implicit. That is, the algorithm must iterate on each time step until an error criterion is met. The details on how the iteration is implemented, and how the algorithm handles step size changes, discontinuities, etc. vary. However, all stiff-stable methods are implicit and therefore iterate to meet the error criterion on each time step.

The difference between explicit and implicit integration is easily described by comparing forward Euler, which is explicit, with backward Euler, which is implicit. The state equations in forward Euler finite difference form can be written as

$$X_{n+1} = X_n + \dot{X}_n h \qquad (7\text{-}1)$$

where
   h = step size

The subscript indicates the time step. The value of the states at the next time step, X_{n+1}, are determined by the values of the states and the derivatives at the present time step.   Backward Euler is written as

$$X_{n+1} = X_n + \dot{X}_{n+1} h \qquad (7\text{-}2)$$

Here the new value of the states X_{n+1} is determined by the present value of the states but also requires the next, or n + 1, value of the derivative. Hence, the algorithm must be iterative.

Most current well tested stiffly stable algorithms require iteration on the complete set of differential equations at one time to achieve successful error control. To achieve efficient computation, the integration step size must be allowed to vary over an extremely large range, e.g., 10^{-10} to 10^{+10} seconds. Because of these two aspects it is not practical to include finite difference integration methods within the model equations. Instead the model must be defined so that all the integration

can be performed by a central integrator. This is compatible with the basic MMS philosophy of using improved "drop-in" software tools as they become available.

Over the last five years, other stiffly stable algorithms have emerged that also partition the model equations automatically and use multiple integration methods in an effort to reduce the overhead required for the implicit integration. Although these methods appear attractive, they have not been proven for MMS type applications.

Section 8

LINEAR ANALYSIS

The MMS is a convenient mechanism for generating a set of equations that mathematically describe a physical process. Simulation is only one type of analysis that can be performed on that set of equations. Other useful analyses can be performed that provide more direct information than simulation at a much lower computer cost. The ACSL and EASY5 versions of MMS incorporate linear analysis routines as follows:

	ACSL	EASY5
● Model linearization (Jacobian calculation)	X	X
● Eigenvalues/Eigenvectors	X	X
● Equilibrium finder	X	X
● Root Locus		X
● Bode plot		X
● Nyquist plot		X
● Stability margins		X
● Optimal controller		X

The first routine (Jacobian calculation) is used by the simulation package itself and provides the linearized model for all the other linear analysis routines. The Jacobian, or linearized model, is generated numerically by perturbing the states a small amount about the current operating point and measuring the effect on the derivatives of all the other states. This can be described by considering a simple nonlinear second order model:

$$\dot{X}_1 = A_{11}X_1 + A_{12}X_2 \tag{8-1}$$

$$\dot{X}_2 = A_{21}X_1 + A_{22}X_2$$

To linearize this model numerically, a small value is first added to X_1 and the change in the derivatives $\dot{X}_1$ and $\dot{X}_2$ is measured. This provides a measurement of the quantity $\partial\dot{X}_1/\partial X_1$ and $\partial\dot{X}_2/\partial X_1$. Then the small value is removed from X_1 and added to X_2, and the change in derivatives is again measured. This provides a value for $\partial\dot{X}_1/\partial X_2$ and $\partial\dot{X}_2/\partial X_2$.

Since

$$\dot{X}_1 = F(X_1, X_2) \text{ and}$$

$$\dot{X}_2 = F(X_1, X_2)$$

the linear model is defined as

$$d\dot{X}_1 = \frac{\partial\dot{X}_1}{\partial X_1} dX_1 + \frac{\partial\dot{X}_1}{\partial X_2} dX_2$$

$$d\dot{X}_2 = \frac{\partial\dot{X}_2}{\partial X_1} dX_1 + \frac{\partial\dot{X}_2}{\partial X_2} dX_2$$

As noted above, the values of the partial derivatives were determined numerically; so the linear model is then defined in matrix form as

$$\dot{X} = A\ X$$

where
$$A = \frac{\partial\dot{X}}{\partial X}$$

For the second order example

$$A = \begin{vmatrix} \dfrac{\partial\dot{X}_1}{\partial X_1} & \dfrac{\partial\dot{X}_1}{\partial X_2} \\\\ \dfrac{\partial\dot{X}_2}{\partial X_1} & \dfrac{\partial\dot{X}_2}{\partial X_2} \end{vmatrix}$$

The linearized model is then used by all the linear analysis routines. The details of the operation and application of the linear analysis routines is beyond the scope of this manual. The reader will find in Reference 11 a good explanation for these analyses. Briefly, however:

Jacobian

The A matrix above is called the Jacobian. It defines the effect of each state on the derivatives of all the other states in the model. In addition to serving as the starting point for the other analyses, the Jacobian is informative in itself. Study of this matrix can identify interaction between model states and is useful for sensitivity studies.

Eigenvalues/Eigenvectors

The eigenvalues of the linear model (Jacobian) are the response modes of the plant model. Each eigenvalue may be a complex (real and imaginary parts) quantity. The real part is the inverse of the time constant of that response mode. Together with the real part, the imaginary part (if present) defines the frequency of the response mode. The eigenvalues can be used to assess model (and plant) stability.

The eigenvector(s) relate the states and the eigenvalues. Each eigenvector corresponds to a particular eigenvalue; its elements identify the sensitivity of each state to that eigenvalue. The eigenvector can provide a closed form time solution for the linear model.

Equilibrium Finder

The equilibrium finder is used to bring the model to a steady state without integrating in time. This normally provides a steady state at reduced computation cost.

Root Locus

The root locus is a control system stability anaysis technique in the time domain. It provides the path (locus) of the model eigenvalues as one model parameter is varied. This may be used to assess model stability sensitivity to that parameter.

Bode Plot

The Bode plot is a control system stability analysis technique in the frequency domain. It is a plot of the gain and phase of the transfer function between two

model variables as a function of frequency. Bode plots are used in control system design to evaluate system sensitivity to noise and other characteristics.

Nyquist Plot

The Nyquist plot is a plot of the gain and phase from the Bode plot on a real-imaginary axis as frequency varies. The Nyquist plot is used to quantitatively assess system stability.

Stability Margin

The stability margin is a quantitative definition of how close the system approaches instability. The stability margin is evident in both the Bode and Nyquist plots.

Optimal Controller

Given a satisfactory performance criterion, the optimal controller package calculates a feedback matrix to minimize system departure from the performance criterion.

For details on the analyses features of each language, the reader is referred to the MMS User Manual for that language or the language user manual.

Section 9

MODULE COMPATIBILITY

The foundation of the MMS is the modularity concept which permits a total plant
model to be constructed from a library of independently developed component models.
To achieve this capability, four critical aspects of module compatibility are
prescribed by MMS:

- physical module boundaries,

- equation compatibility,

- intermodule information transfer, and

- variable nomenclature.

These items are briefly discussed below:

9.1 PHYSICAL MODULE BOUNDARIES

The MMS modules mathematically describe the dynamic operation of physical plant
components. Therefore, all the describing equations must be contained within that
module, and conversely, all modules must have physically definable boundaries. The
module boundaries can be a portion of a larger component or a collection of several
components. But in any case, the boundaries must be easily identified within the
physical process. Furthermore, all module outputs must be calculated based on the
energy, mass, and momentum exchanges within the module and the fluid properties at
the boundaries. The outputs must not be calculated as a function of variables
within any other modules - not even the adjacent modules.

This requirement sounds trivial. However, it is commonly violated in order to
improve computational efficiency at the sacrifice of modularity. For example,
pressure losses through several components are frequently lumped into one pressure
loss to avoid using several continuity equations. If a module is removed or a new
one added, the pressure loss equation, which was calculated separately, must also be
corrected. This leads to error prone and confusing changes. Another example is

lumping mass changes for all the components in a nuclear primary loop into the
pressurizer module. Again this violates modularity to increase computational
efficiency.

The MMS gains computational efficiency by tailoring the numerical integration method
and equation formulations rather than violation of modularity. This is discussed in
more detail in Section 7 of this manual.

9.2 EQUATION COMPATIBILITY: RESISTIVE AND STORAGE COMPONENTS

The most difficult aspect of providing convenient modularity is assuring the compat-
ibility of the complete set of equations resulting from combining individual
modules. This means that two adjacent modules must not solve for the same variable
(an overdefined system), and no system variable must be left undefined resulting in
either an implicit set of equations or an indeterminant set. These problems are
easily avoided in the MMS by use of the concept of resistive and storage modules.

Any module that contains a flow calculation as a function of pressure drop and does
not contain the dynamic continuity equation is considered purely resistive because
the flow "resistance" creates the pressure drop. This is represented by the dynamic
or steady state momentum equation. For discussion here we will assume a simple
incompressible pipe module described by the steady state momentum equation (eqn.
4-8) with no elevation difference between inlet and outlet:

$$w_e = C \sqrt{\rho_e (p_e - p_\ell)} \qquad\qquad (9\text{-}1)$$

As can be seen from 9-1, both the upstream and downstream pressures must be known to
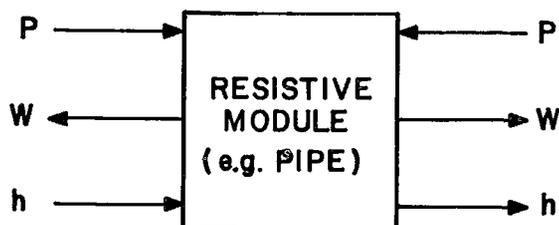solve for the flow. This is shown schematically in Figure 9-1.

Figure 9-1. Schematic of Resistive Module

To determine component compatibility, the storage module must be examined. Any module whose dominant effect on the system is mass or energy storage rather than pressure loss is considered to be a storage module.

For discussion here, a simple tank model is an example of a pure storage module and described by the continuity equation:

$$\frac{d\rho_e}{dt} = \frac{W_e - W_\ell}{V} \qquad\qquad (9\text{-}2)$$

From 9-2, the density calculation requires the upstream and downstream flows as inputs. Hence a storage component is shown schematically in Figure 9-2.
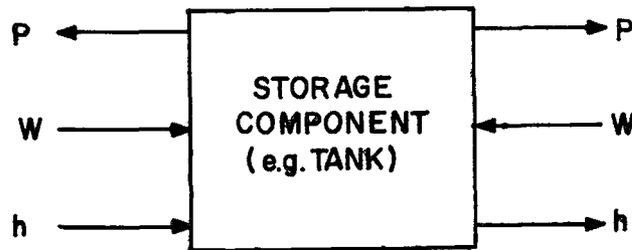

Figure 9-2. Schematic of Storage Module

From both the equations and the schematics, it is apparent that two resistive modules cannot be in series because they would both attempt to calculate the same flow and the intermediate pressure would not be determined. Likewise, two storage components cannot be in series because both would be trying to calculate the same pressure but the intermediate flow would not be available. However, if the resistive modules alternated with the storage modules along the flow path, a complete compatible set of equations would result.

Modules that include both pressure drop and storage calculations also exist and in fact are more common than purely one type. These are called either resistive-storage or storage-resistive modules. As discussed in Section 3, the continuity equation is written to represent the density or pressure at the leaving port. Consequently, the combined resistive-storage components designate the resistive component first followed by the storage component. This is shown schematically in Figure 9-3.

```
   P  ──────►┌──────────────────────┐────►  P
   W  ◄────── │    RESISTIVE –       │ ◄──── W
   h  ──────► │ STORAGE COMPONENT    │ ────► h
             └──────────────────────┘
```
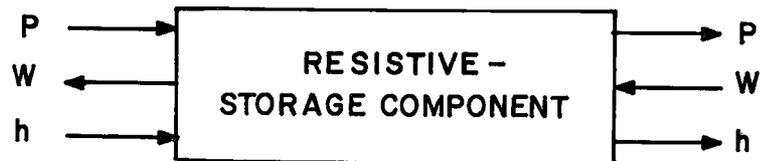
Figure 9-3.   Schematic of Resistive-Storage Component

Where the module is storage-resistive, the directions of information transfer of pressure and flowrate are reversed. A convenient mechanism has been devised to ensure that the order in which the modules are connected is compatible with these information flows. Resistive modules include a resistive symbol (─√√√√─) on the User Worksheet interface diagram. Storage modules include a storage symbol (─O─). Resistive-storage modules include a combined symbol (─√√√√─O─), and storage-resistive modules include the symbol (─O─√√√√─). Generating the system model requires only that modules be connected in a sequence that alternates the resistive and storage symbols.

An ideal set of modules would be all combined resistive-storage type or storage-resistive. Then all modules would always interface with all other modules and the resistive/storage designators would be superfluous. This approach has a philosophical appeal but, unfortunately, major practical limitations. As smaller pressure drops are modeled (e.g., form losses at tank inlets) and smaller storage volumes are modeled (e.g., the storage in valve casings), the equations become numerically sensitive and consequently increase computational costs. Although the MMS integration methods are well suited to handle this type of problem, they place an unnecessary cost burden on the majority of applications -- in both engineering and computer costs. Consequently, the MMS provides the flexibility to represent only those aspects of a component that are significant. If modules are to be used in a wide range of applications, multiple modules with different degrees of complexity are easily defined without violating the basic modularity concepts or imposing high costs on all applications.

For some system models, it will be desirable to connect two resistive modules in series. Since this creates an indeterminate set of equations, a simple connective node is provided to calculate the missing pressure between the two. This node is a convenient means of meeting the modularity requirements without affecting the simulation results.

9.3 INTERMODULE INFORMATION TRANSFER

Module information transfer must support the concept of resistive and storage modules. At least three process variables are required to fully define a flow stream. The MMS uses pressure, flow, and enthalpy as the three required variables. However, since temperature and density are both frequently desired outputs and/or required simulation variables, they also are part of the information contained in the module interconnection vector. Hence the resulting information transfer for resistive, storage, resistive-storage and storage-resistive modules are as shown in Figure 9-4. The variables on the left side are upstream properties, those on the right are downstream properties. Arrows pointing into the module are computational inputs; those pointing out are outputs.
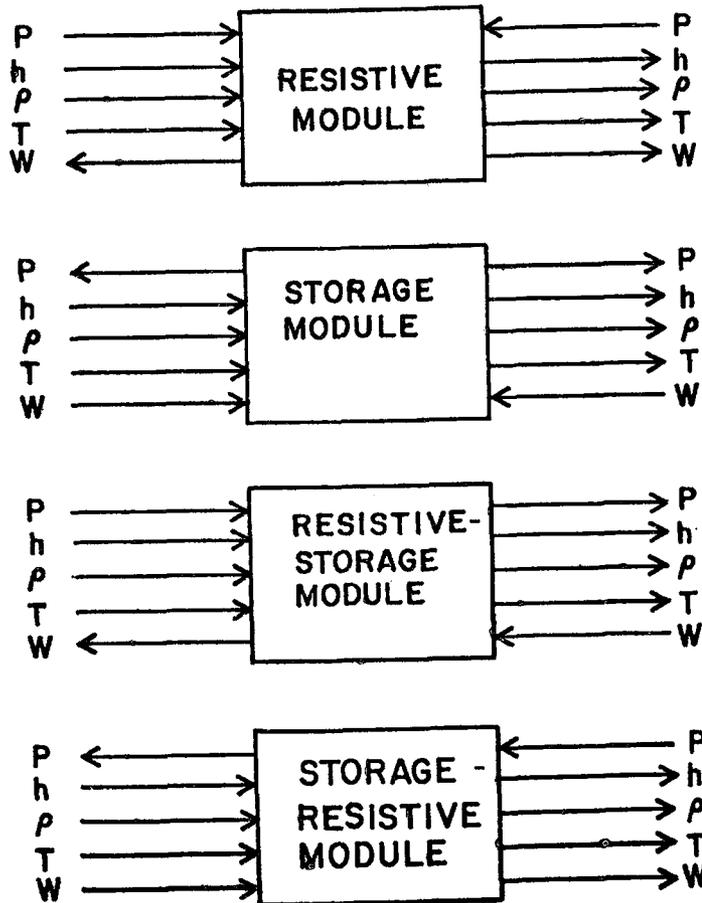
Figure 9-4. Interconnection Schematic For MMS Modules

9.4 MMS NOMENCLATURE

The MMS nomenclature reinforces the modularity concept. In general, a nomenclature should facilitate reading code and output, follow a pattern so the user doesn't have to "remember" variable names, prevent name conflicts, and provide a base for automated functions such as automatic module interconnections and variable name generation. The MMS nomenclature has been reviewed by many sources including the ISA Power Plant Dynamics Committee and modified to assure an acceptable convention.

The MMS nomenclature uses a six character name where the first character alone will indicate its general category. These reserved first character identifiers are listed below:

A	Area
C	Control System Variables
D	Derivatives
E	Electrical Variables (e.g., volts, amperage)
F	Neutron Flux
G	Concentration, ratio, efficiency
H	Enthalpy
I	Initial Conditions
J	Power
K	Miscellaneous Coefficients and Constants
L	Level
M	Mass
N	Speed
O	Validity Flags
P	Pressure
Q	Heat Flux
R	Density (rho)
S	Entropy
T	Temperature
U	Internal Energy
V	Viscosity/Volume
W	flow
X	Steam Quality

Y   Position/Stroke

Z   Reserved for internal uses.
     Cannot be used for variable name.

Having a one character assignment as specified above will allow the user to take advantage of sorting routines available, facilitate reading a program listing, expedite changes in the program and most importantly prevent conflicting names of process variables.

The remainder of the nomenclature differs somewhat between the ACSL and EASY5 versions of MMS. The user should consult the MMS User Manual for a detailed discussion of the nomenclature for the particular language.

Section 10

MULTIPLE COMPONENT REPRESENTATIONS

The MMS philosophy and structure allows multiple components to be grouped into one module for convenience and computational efficiency. For example, many valves in power plants have significant pipe sections upstream and/or downstream. To reduce the number of modules a user must call if both the valve and pipe are to be modeled, and to reduce computational costs, the resistance and inertance for both can be included in one module by calculating an equivalent resistance and an equivalent inertance.

Components connected by parallel flow paths can also be combined into one module by calculating equivalent resistances and inertances. Parallel feedwater heaters provide a good example. Since parallel heaters typically share the load equally, it is frequently desirable to model only one equivalent heater to reduce computational costs. The method MMS uses for calculating equivalent parameters is described below.

10.1 CONDUCTANCE NETWORKS

The steady state and dynamic momentum conservation relation can be solved for several pipes, valves, or other resistive components together. MMS associates a flow conductance, C, with every component characterized as Resistive. This conductance defines the component's steady-state momentum conservation response: its pressure-flow characteristics. Similarly, an inertance may be associated with the component which defines its dynamic momentum conservation response. For any flow stream, or network comprising any number of components, which may be treated as incompressible (and steam may be treated as incompressible if the pressure drop is less than ten percent of the absolute pressure), the conductances and inertances of all the components may be combined into a single conductance and a single inertance which will represent the entire network. The equivalent flow conductance is calculated from the steady state momentum equation (eqn 4-8).

10-1

$$w_e = C \sqrt{\rho_e(p_e - p_\ell) + \frac{g}{g_c} \rho_e^2 (z_e - z_\ell)}$$ (4-8)

Where C = flow conductance

Figure 10-1 shows two resistive components in parallel.
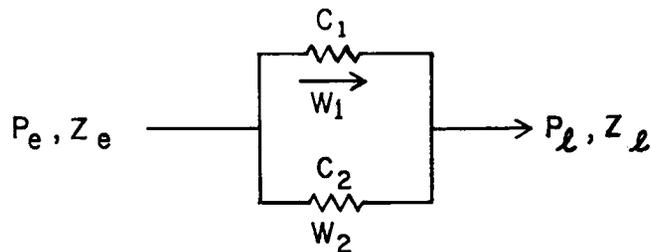

Figure 10-1. Parallel Resistive Components

Since the total flow must equal the sum of the parallel flows,

$$w_T = w_1 + w_2$$ (10-1)

$$w_1 = C_1 \sqrt{\rho_e(p_e - p_\ell) + \frac{g}{g_c} \rho_e^2 (z_e - z_\ell)}$$ (10-2)

$$w_2 = C_2 \sqrt{\rho_e(p_e - p_\ell) + \frac{g}{g_c} \rho_e^2 (z_e - z_\ell)}$$ (10-3)

$$w_T = (C_1 + C_2) \sqrt{\rho_e(p_e - p_\ell) + \frac{g}{g_c} \rho_e^2 (z_e - z_\ell)}$$ (10-4)

Hence the equivalent conductance is

$$C_{eq} = C_1 + C_2$$ (10-5)

For components in parallel

$$C_{eq} = \sum_{i=1}^{n} C_i \qquad\qquad (10\text{-}6)$$

Figure 10-2 shows two resistive components in series.
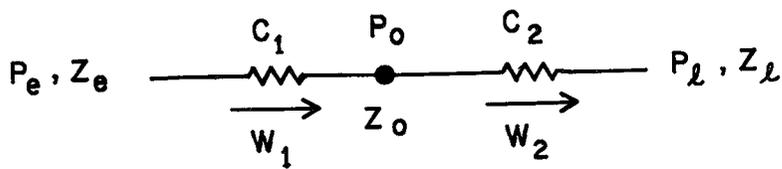

Figure 10-2. Series Resistive Modules

Assuming the flow is incompressible (or nearly so)

$$w = w_1 = w_2 \qquad\qquad (10\text{-}7)$$

Then

$$\left(\frac{w}{C_1}\right)^2 = \rho(p_e - p_0) + \rho^2 \frac{g}{g_c} (z_e - z_0) \qquad\qquad (10\text{-}8)$$

$$\left(\frac{w}{C_2}\right)^2 = \rho(p_0 - p_\ell) + \rho^2 \frac{g}{g_c} (z_0 - z_\ell) \qquad\qquad (10\text{-}9)$$

Adding 10-8 and 10-9 and solving for the flow gives

$$w = \frac{1}{\sqrt{\frac{1}{c_1^2} + \frac{1}{c_2^2}}} \sqrt{\rho(p_e - p_\ell) + \rho^2 \frac{g}{g_c} (z_e - z_\ell)}$$ (10-10)

In the general case then, the equivalent conductance for n components in series is

$$C_{eq} = \frac{1}{\sqrt{\sum_{i=1}^{n} \frac{1}{c_i^2}}}$$ (10-11)

10.2 INERTANCE NETWORKS

When the dynamic momentum equation must be used, an equivalent inertance can be calculated for series and parallel component networks. Applying the dynamic momentum equation (eqn 4-5) to the series components in Figure 10-2 gives

$$\frac{dw_1}{dt} = \frac{A_1}{L_1} \left[g_c (p_e - p_0) - g_c \frac{(w_1/C_1)^2}{\rho} + \rho g (z_e - z_0) \right]$$ (10-12)

$$\frac{dw_2}{dt} = \frac{A_2}{L_2} \left[g_c (p_0 - p_\ell) - g_c \frac{(w_2/C_2)^2}{\rho} + \rho g (z_0 - z_\ell) \right]$$ (10-13)

Since $w = w_1 = w_2$ the above two equations can be added giving

$$\left[\left(\frac{L_1}{A_1}\right) + \left(\frac{L_2}{A_2}\right) \right] \frac{dw}{dt} = \left[g_c (p_e - p_\ell) + g \rho(z_e - z_\ell) - \frac{g_c w^2 \left[\left(\frac{1}{C_1}\right)^2 + \left(\frac{1}{C_2}\right)^2 \right]}{\rho} \right]$$ (10-14)

The resistance term on the right hand side can be simplified in terms of an equivalent conductance using Equation 10-11.

10-4

Then

$$\frac{dw}{dt} = \frac{\left[g_c \ (p_e - p_\ell) + g \ \rho(z_e - z_\ell) - \frac{g_c\left(\frac{w}{C_{eq}}\right)^2}{\rho} \right]}{\left[\left(\frac{L_1}{A_1}\right) + \left(\frac{L_2}{A_2}\right) \right]}$$

(10-15)

The equivalent inertance is

$$\left(\frac{L}{A}\right)_{eq} = \left(\frac{L_1}{A_1}\right) + \left(\frac{L_2}{A_2}\right)$$

(10-16)

In general, for n components in series:

$$\left(\frac{L}{A}\right)_{eq} = \sum_{i=1}^{n} \left(\frac{L}{A}\right)_i$$

(10-17)

Re-examining the parallel flow configuration and applying the momentum equation to each element:

$$\frac{dw_1}{dt} = \frac{A_1}{L_1} \left[g_c \ (p_e - p_\ell) + g \ \rho(z_e - z_\ell) - \frac{g_c\left(\frac{w_1}{C_1}\right)^2}{\rho} \right]$$

(10-18)

$$\frac{dw_2}{dt} = \frac{A_2}{L_2} \left[g_c \ (p_e - p_\ell) + g \ \rho(z_e - z_\ell) - \frac{g_c\left(\frac{w_2}{C_2}\right)^2}{\rho} \right]$$

(10-19)

Since: $w = w_1 + w_2$

$$\frac{dw}{dt} = \left[g_c \ (p_e - p_\ell) + g\rho \ (z_e - z_\ell)\right]\left(\frac{A_1}{L_1} + \frac{A_2}{L_2}\right) - \frac{g_c\left(\frac{w_1}{C_1}\right)^2}{\rho} \frac{A_1}{L_1} - \frac{g_c\left(\frac{w_2}{C_2}\right)^2}{\rho} \frac{A_2}{L_2}$$

(10-20)

10-5

It is approximately true that:

$$\frac{\left(\frac{w_1}{C_1}\right)^2}{\rho} = \frac{\left(\frac{w_2}{C_2}\right)^2}{\rho} = \frac{\left(\frac{w}{C_{eq}}\right)^2}{\rho} \qquad (10\text{-}21)$$

$$\frac{dw}{dt} = \left[g_c \left(p_e - p_\ell \right) + g\rho \left(z_e - z_\ell \right) - \frac{g_c \left(\frac{w}{C_{eq}}\right)^2}{\rho} \right] \left(\frac{A_1}{L_1} + \frac{A_2}{L_2} \right) \qquad (10\text{-}22)$$

The equivalent inertance of the two is:

$$\left(\frac{L}{A} \right)_{eq} = \frac{1}{\left(\frac{A_1}{L_1} + \frac{A_2}{L_2} \right)} \qquad (20\text{-}23)$$

In general, for n components in parallel:

$$\left(\frac{L}{A} \right)_{eq} = \frac{1}{\sum_i^n \left(\frac{A}{L} \right)_i} \qquad (10\text{-}24)$$

Section 11

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EPRI CS/NP-2989

Below are five index cards that allow for filing according to the four cross-references in addition to the title of the report. A brief abstract describing the major subject area covered in the report is included on each card.

EPRI

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RP1184-2,
RP1163-1
Final Report
March 1983

Modular Modeling System (MMS): A Code for the Dynamic Simulation of Fossil and Nuclear Power Plants   Overview and General Theory

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4. Analysis and Testing Program

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