Technical Paper

Latest developments in natural circulation boiler design

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Presented to
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THE LATEST DEVELOPMENTS IN NATURAL CIRCULATION BOILER DESIGN

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INTRODUCTION

In the last eight years the predominant trend in the U.S. utility industry for fossil fired units has been toward the 2400 psi cycle (Fig. 1). The percentage of units bought for the 2400 psi cycle has steadily increased and in the last five years has averaged more than 70 percent of units ordered. All of these units are drum type boilers.

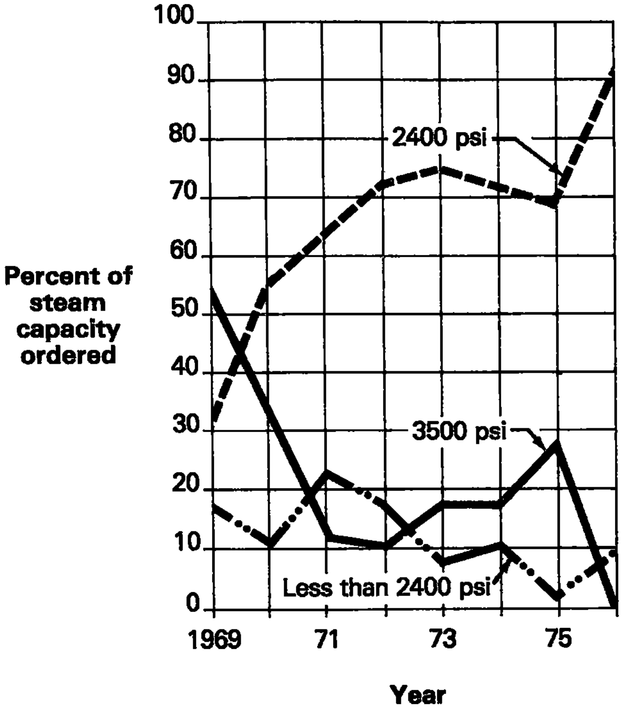

Fig. 1 Distribution of orders by pressure, USA

Two methods of circulation are used with drum boilers for furnace wall cooling - - - natural circulation or pump assisted circulation. There is a growing preference for the natural circulation method for use with the 2400 psi cycle. This trend to natural circulation is undoubtedly the result of good operating experience.

Advances in research and development, coupled with extensive experience, have led to numerous improvements in the natural circulation design that have increased boiler reliability. The development by Babcock & Wilcox of internally ribbed tubes has made possible the extension of natural circulation to drum operating pressures well above those attainable with internally smooth tubes and pump assisted circulation. The unique combination of ribbed tubes and natural circulation presents a simple, efficient and reliable method of furnace wall cooling.

OBJECTIVE OF CIRCULATION IN FURNACE WALL TUBES

The furnace enclosure is one of the most critical components of a steam generator and must be conservatively designed to assure high boiler availability. The furnace configuration and its size are determined by combustion requirements, fuel characteristics, emission standards, and the need to provide a uniform gas flow and temperature entering the convection heat absorbing surfaces to minimize ash deposits and superheater metal temperatures. The tube sizes and enclosure walls are determined by the type of circulation and the boiler capacity. The tube and membrane materials must provide for long term life compatible with the expected pressure and thermal stresses.

The circulation objective is to assure sufficient cooling of the furnace tubes during all operating conditions with an adequate margin of reserve for transient upsets. Furnace tubes are protected against overheat from the high radiation heat flux when stable nucleate boiling is maintained on the internal tube surface by the proper flow distribution to all circuits commensurate with heat absorption. Adequate circulation prevents excessive metal temperatures or temperature differentials in the furnace wall tubes that could cause failures due to overstressing or corrosion.

Circulatory systems for furnace enclosure must be designed to criteria and limits established by data from laboratory experiments, field tests, and operating experience. In the past, the circulation ratio, defined as the weight of circulating flow divided by the weight of steam generated, has been accepted as an empirical design criterion for evaluating the performance of circulation systems. Actually, the most important circulation criterion in drum boilers is the prevention of conditions that could lead to a "departure from nucleate boiling" (DNB).

RESEARCH OF DNB LIMITS(1)

DNB is a combined phenomenon of fluid dynamics and heat transfer. The exact mechanism is not fully known because of the multiplicity of influencing parameters and the complexities inherent in two-phase flow with heat addition. Babcock & Wilcox has conducted, during the past 25 years, extensive research in boiling heat transfer to establish the design limits for DNB.

In a typical test, water is introduced at one end of a tube and steam leaves the other end as heat is added along the tube. In Fig. 2, the temperature of the inside of the tube is plotted against the steam quality, percent steam by weight (% SBW), of the fluid as it moves along the tube length. Initially, the inside surface temperature of the tube is very close to the bulk fluid temperature. When proceeding along the length of the tube, this differential remains quite constant as long as nucleate boiling is present but, then, suddenly and sharply increases when DNB occurs. This point, D, is the location of DNB in an internally smooth tube.

RIBBED TUBES PREVENT DNB IN BOILERS(2)

B&W tested a large number of devices, including twisters, springs and various grooved, ribbed and corrugated tubes to inhibit or delay the onset of DNB. The most satisfactory overall performance was obtained with tubes having properly designed helical ribs on the inside surface (Fig. 3) which generate a swirling flow. The resulting centrifugal action forces water droplets towards the inner tube surface and prevents the formation of a steam film. The internally ribbed tube maintains nucleate boiling at much higher steam qualities (% SBW) and with much lower mass velocities than those in smooth bore tubes, as shown by points D-1 and D in Fig. 2.

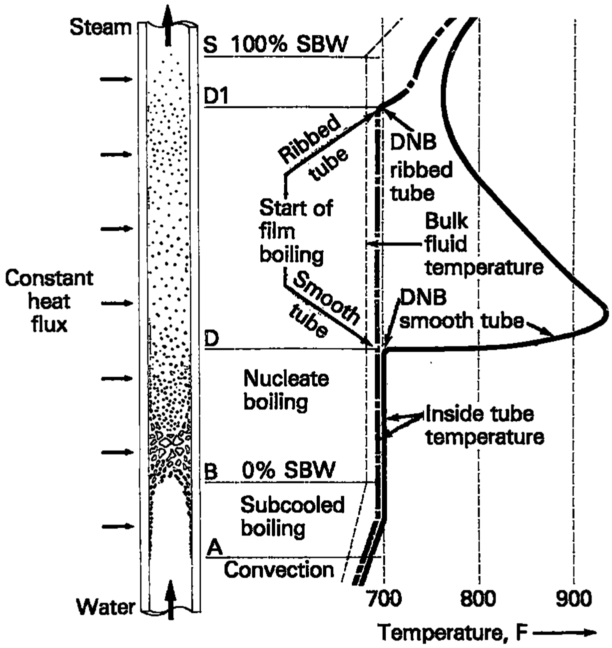

Fig. 2 Effect of type of boiling on tube metal temperature at 2800 psia

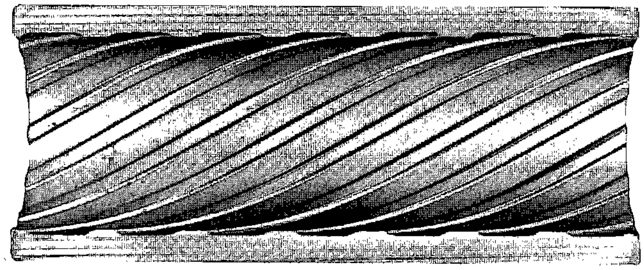

Fig. 3 Multilead ribbed tube

The friction pressure drop of the ribbed tubes is only slightly greater than that of cold finished smooth bore tubes and, therefore, has an insignificant effect on the circulation flow rates. The outstanding performance of the ribbed tubes has been confirmed by the British CEGB research center.(3).

INTEGRITY OF RIBBED TUBES

The multi lead ribbed tubes used in B&W natural circulation boilers are heat treated to effectively remove any residual stresses induced during the formation of ribs. The corners at the rib to tube junction are adequately rounded to minimize stress concentrations. Under cycling boiler operation the combined pressure and thermal stresses of the ribbed tube are below the endurance limit.

The integrity of ribbed tubes has been demonstrated by extensive utility service. This type of tube, first used to correct DNB and other circulation problems in operating units, has performed satisfactorily for 19 years. Samples removed periodically for inspection indicate no internal corrosion and no selective or excessive deposits.

PARAMETERS AFFECTING DNB

The onset of DNB is influenced by geometrical and operational (thermodynamic) factors. Geometrical factors include tube ID, wall construction (tangent tubes, membrane wall, tube spacing, tube screen), internal surface conditions (smooth tubes, ribbed tubes, deposits, etc.) and tube position (vertical, inclined, curved). Operational factors include pressure, local quality % SBW or subcooling (enthalpy), mass velocity, heat flux, water chemistry, etc. Extensive experimental data covering a wide range of these parameters have been collected by B&W, and it has been determined that in long tubes DNB depends primarily on the local conditions.

For a given boiler design many of these parameters are fixed and the principal concerns are the combined effects of pressure, heat flux and steam quality (% SBW) on the required circulation mass velocities to prevent the onset of DNB. Generally, in a utility boiler, the required mass velocity increases with pressure, with heat flux, and with quality. Figures 4, 5 and 6 show the great advantage of the ribbed tubes over smooth tubes. Figures 6 shows the effect of pressure and local quality on the required mass velocity to avoid DNB in membrane wall tubes at a heat flux comparable to the maximum upset absorption rates encountered at the top of the burner zone in large coal fired utility boilers. The maximum local quality at the top of the burner zone is usually between 15 and 25% SBW.

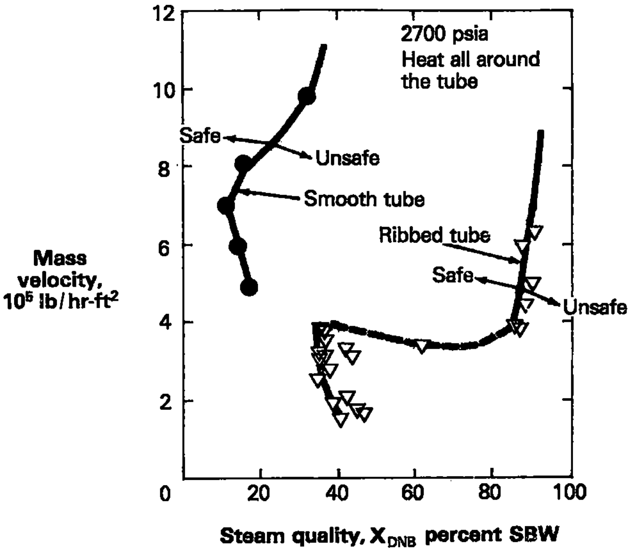

Fig. 4 Effect of quality on required mass velocity to avoid DNB

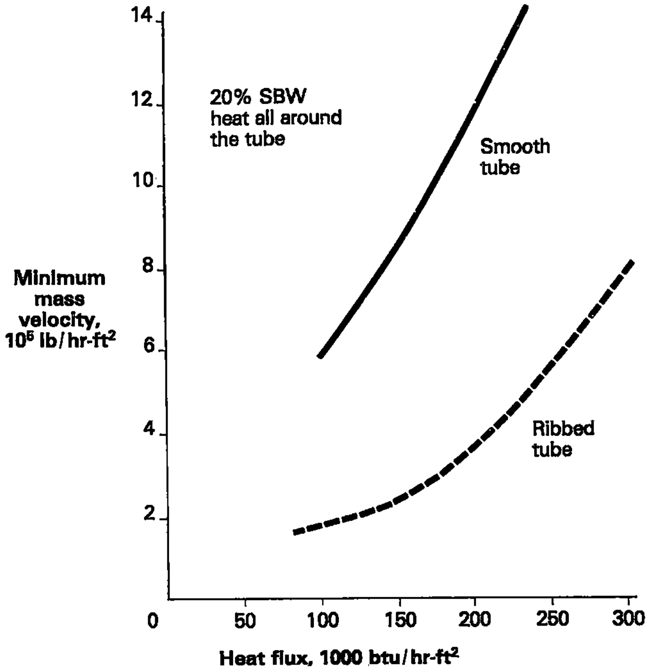

Fig. 5 Effect of heat flux on required mass velocity to avoid DNB

Above 2700 psi, the pressure becomes an increasingly critical consideration in regard to the required mass velocity, especially for smooth tubes. Smooth tubes also are sensitive to local quality — the higher the quality, the higher the required mass velocity. In contrast, ribbed tubes require less than one half of the mass velocity and can withstand much higher local steam qualities than smooth tubes. These advantages of ribbed tubes provide a great margin of safety, even when operating at pressures as high as 3000 psi.

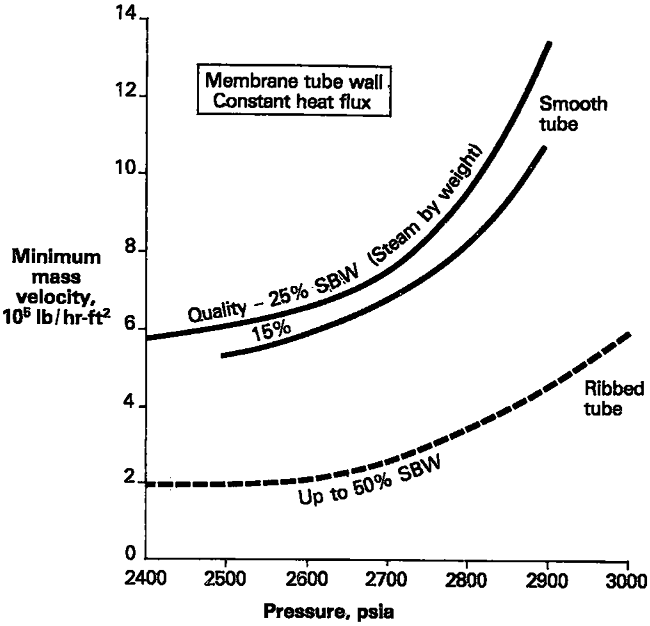

Fig. 6 Effect of pressure on required mass velocity to avoid DNB

PRINCIPLES OF NATURAL CIRCULATION

The general principles of natural circulation are well known to power engineers. There exists, however, a misconception that natural circulation is not possible at pressures approaching or exceeding the critical pressure because the density ratio of water to steam approaches unity at the critical point. In principle, there is no pressure limit for natural circulation, although the unity density ratio, at and above the critical point, does preclude separation of phases. Natural circulation is possible even at supercritical pressures, but without a drum level.

Natural circulation in a boiler circulation loop (Fig. 7) relies only on the difference between the mean density of the fluid (water) in the downcomers and the mean density of the fluid (steam water mixture) in the heated furnace tubes. The difference in these densities provides the pumping drive that causes flow in the loop. The actual pumping head is the difference between the total gravity head in the downcomer and the integrated (sum of) gravity heads in the upcoming legs of the loop containing the heated tubes. The pumping head must balance the sum of the flow losses due to friction, shock, and acceleration throughout the entire loop.

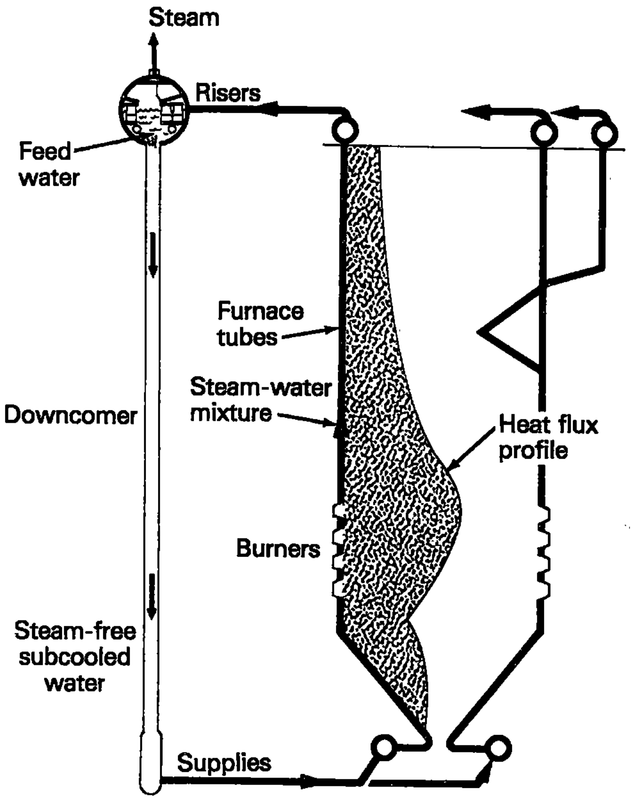

Fig. 7 The circulation loop

The basic natural circulation equation can be expressed as follows:

PUMPING HEAD = SUM OF PRESSURE LOSSES

$$\frac{H \cdot \rho_{DC}}{144} - \int_{O}^{H} \frac{\rho \cdot dH}{144} = \Sigma(\Delta P_{friction} + \Delta P_{shock} + \Delta P_{accel})$$

H = Height from inlet header to drum water level, ft.

ρ_{DC} = Mean fluid density in downcomer, lb/ft³

ρ = Actual local density in upflowing leg of loop, lb/ft³

ΔP = Pressure loss, psi.

The nonhomogeneous nature of the two-phase flow of steam-water mixtures and the heat absorption pattern must be considered in the determination of local densities and pressure losses.

For any given heat input a state of equilibrium exists at which the system circulates at a constant rate, and the higher the heat input (or boiler load) the higher the circulation flow.

Normally, the water in the downcomer of high pressure boilers is subcooled approximately 15 to 22 degrees F as a result of mixing the subcooled feedwater from the economizer with the water at saturation temperature separated in the steam drum. The fluid in the upflowing furnace wall tubes is a steam and water mixture with a mean density much lower than the density of water in the downcomer. The effect of pressure on these densities for a typical high pressure boiler is shown in Fig. 8. The resulting large difference in densities, that provides the natural circulation pumping action, persists for pressures approaching critical pressure and beyond.

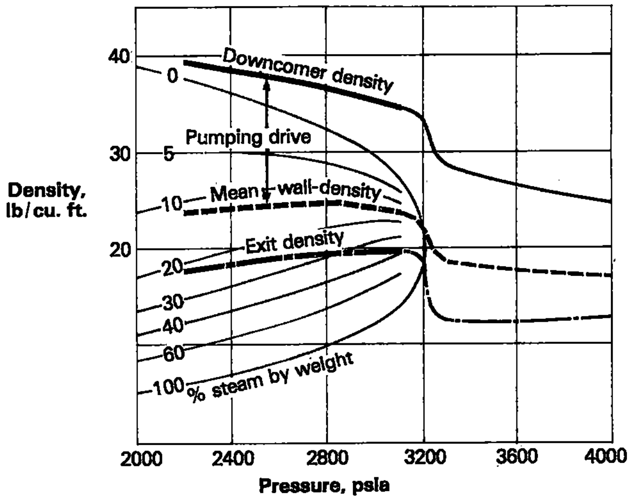

Fig. 8 Effect of pressure on density in downcomers and tube walls at maximum firing rate

The potential for natural circulation flow remains very high even at pressures of 3100 psi. This is shown in Fig. 9 by plotting weight flow and velocity as a function of pressure. At the high subcritical pressures, the water velocity in the furnace tubes actually increases with rising pressure due, mainly, to the decrease in the density of saturated water. This offers an advantage over pumped circulation where the velocity in tubes remains constant, independent of pressure, because the pumps deliver essentially a constant volume of water.

The distribution of the available pumping head for a natural circulation boiler operating at 2850 psi drum pressure is shown in Fig. 10.

The effect of load on natural circulation weight flow in a drum boiler is depicted in Fig. 11. At variable pressure operation, the circulation flow rate increases with reduced load. At constant pressure, the flow drops only slightly at reduced loads; but with ribbed tubes the resulting mass velocities are more than adequate to prevent DNB.

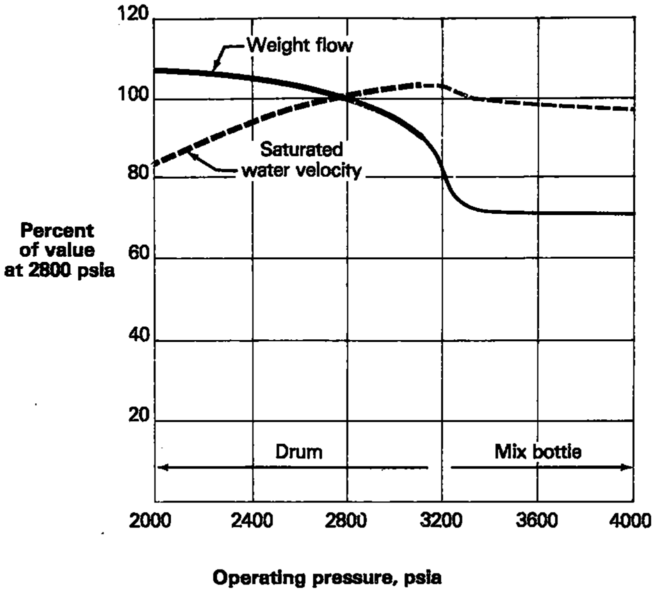

Fig. 9 Effect of pressure on natural circulation flow at constant firing rate

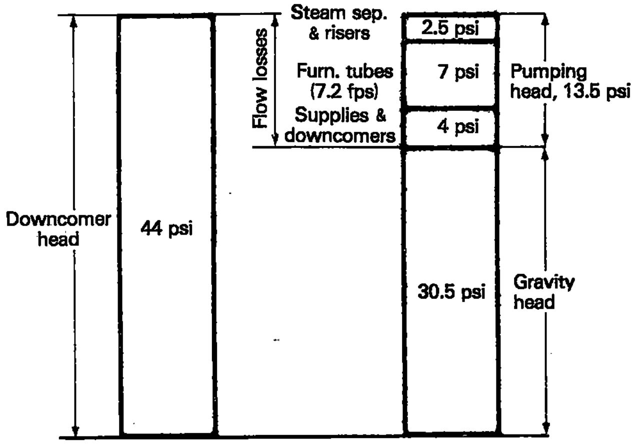

Fig. 10 Available pumping head for natural circulation at 2850 psi drum operating pressure

In B&W designs, when firing a boiler at 10 to 15 percent of full load input during the startup period, the circulation rate in the tubes is equivalent to about 50 to 60 percent of the full load flow rate and all tubes closely approach the saturation temperature.

OPTIMIZATION OF CIRCULATION

An examination of the circulation equation indicates the following positive measures for optimization of circulation that are used in B&W designs to assure high flow rates . . .

1. Increasing the furnace height tends to increase

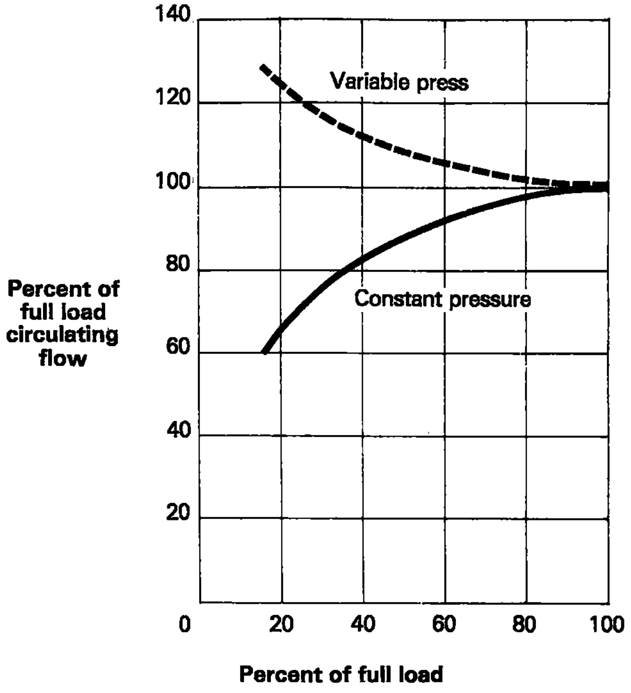

Fig. 11 Effect of load on circulating flow

the pumping head, but it also tends to increase the pressure losses. Circuit design must be coordinated with unit height.

2. The fluid density in the downcomer should be as high as possible. This is achieved by highly efficient cyclone steam separators having low "carry under" of steam and low pressure drop. Feedwater leaves the economizer at sub-saturation temperatures and is properly introduced into the drum to completely quench any steam entrained in the drum water before it reaches the downcomers. Vortex inhibitors are installed at the downcomer inlets to avoid entrainment of steam. The water level is sufficiently high above the downcomer inlets to prevent steam "drawdown".

3. The mean density in the heated tubes should be as low as practical. Locating burners low in the furnace reduces the mean density. Reducing the circulation ratio provides a higher percent steam by weight (% SBW) and, thus, reduces the density. High % SBW in smooth bore tubes, however, cannot be permitted at high pressures because of the danger of DNB. With ribbed tubes, much higher steam qualities can be safely tolerated and even at reduced circulation ratio the DNB safety margins are considerably increased in comparison to smooth tubes.

4. The system pressure losses should be kept as low as practical. Large flow areas are provided for the heated furnace tubes and for the external circulatory system. The wall tubes are usually 2½" to 3" outside diameter and low alloy material is used in the high heat flux areas to reduce tube wall thickness and minimize thermal stresses. The drum internals for steam separation are designed and sized for very low pressure drop (less than 0.4 psi) through the use of tangential cyclone separators where all of the kinetic energy is utilized for separation.

The water level along B&W drums remains relatively uniform due to: a) the large drum diameter (72" ID), b) the high water inventory resulting from the normal water level above the drum centerline, and c) the directional spouts at the outlet of the cyclone separators directing the flow towards the downcomers.

MANY SMALL CAPACITY BURNERS EQUALIZE ABSORPTION PATTERN

Knowledge of the furnace absorption rate pattern, both vertical and peripheral, is most important in the circulation design of large furnaces. The absorption distribution profile depends on a) the fuel and ash deposition characteristics b) the type of burners and their relative location, c) the heat input per plan area of furnace, d) the burner zone heat release rate, e) the excess air, and f) gas recirculation where applicable.

The general shape of the inherent vertical and lateral absorption rate pattern has moderate variation with load or firing rate and is consistently reproducible.The magnitude of the local heat flux in the furnace does change, however, with the heat input. Absorption tests have shown that an additional non-continuous variation of local heat absorption rate at each load is superimposed over the inherent, steady pattern. The non-continuous heat absorption deviations are due to operational variables such as unbalanced firing, changing slagging conditions, load swings, selected sootblowing, pulverizers out of service, fan outages, etc. The magnitude of the heat upset factor depends on operational conditions, firing arrangements and fuel slagging characteristics.

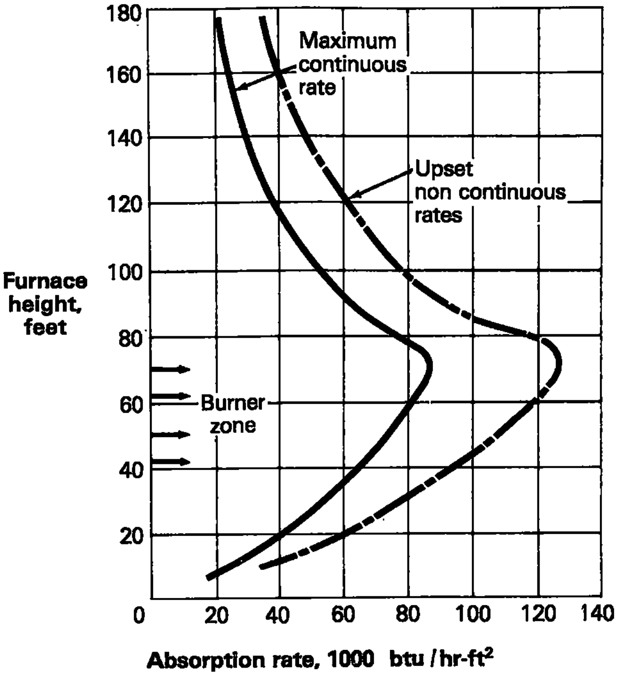

Fig. 12 Heat absorption rates along furnace front wall tubes

Fig. 12 shows the maximum continuous heat absorption rate and the highest upset non-continuous heat absorption rate over the furnace height calculated for the unit shown in Fig. 13. The peripheral inherent heat absorption distribution is shown in Fig. 14. This pattern remains similar even when pulverizers are removed from service, since each pulverizer feeds burners of the same level across the entire furnace width. In large B&W natural circulation furnaces, the use of many low heat input dual register circular burners equalizes the heat absorption pattern of the furnace walls.

PROVISIONS FOR PROPER FLOW DISTRIBUTION

B&W natural circulation boilers are designed to inherently provide adequate flow rates to the various parallel circuits. Tubes of the same length are combined into panels with separate headers. They have a complementary set of supplies and risers sized on the basis of the heat pickup pattern inherent to the relative location of the tubes in the furnace. If necessary, the flow also can be adjusted by increasing the tube size in the upper furnace. Because of the relatively large tube size and the closely controlled internal diameters of ribbed tubes, the pressure drop variations due to manufacturing tolerances are small and have little effect on flow distribution to adjacent furnace tubes.

This method of flow distribution to wide open circuits is superior to the use of small orifices which, in time, can build up a deposit layer even with high purity boiler water. The deposit build up increases the pressure drop of the orifices and affects the flow distribution.

During startups, the uniform temperatures in B&W natural circulation units are obtained by placing the discharge of most of the risers from each circuit below the normal water level. This provides positive circulation in all parts of the boiler during startup and shutdown.

The flow calculations for each furnace circuit are based not only on the expected heat absorption rate along the tubes, but also on two possible extreme heat absorption rates. The lowest heat absorption rate determines the expected minimum mass velocity while the maximum heat absorption rate determines the highest quality; and both values are used to establish the DNB limit of the circuit.

The typical values for average and maximum steam qualities over the height of the tubes in the furnace are shown in Fig. 15. Because of the compensating feature of natural circulation — increased flow when more heat is absorbed — the spread between the maximum and average steam quality is smaller with natural circulation than with pumped circulation. The top of the burner zone where the heat flux is the highest is the most critical location in the furnace. The maximum quality at this level is usually about 20 percent SBW.

LARGE MARGIN OF SAFETY WITH RIBBED TUBES

For any given operating pressure and minimum mass velocity, there is a critical steam quality for each heat flux along the tube at which DNB will occur. Fig. 16 shows the maximum allowable steam quality to avoid DNB in smooth bore tubes for the upset heat flux pattern along the tube (from Fig. 12) for two mass velocities. The dotted line represents a mass velocity of 8 x 10^5 lb/hr-ft^2, which is the maximum attainable with natural circulation in a circuit with the lowest heat absorption at a circulation ratio of 4.0. The dash line represents a mass velocity of 11 x 10^5 lb/hr-ft^2, which is the value normally provided by pumped circulation. The solid line represents the maximum expected steam quality shown in Fig. 15. The available margin of safety is indicated

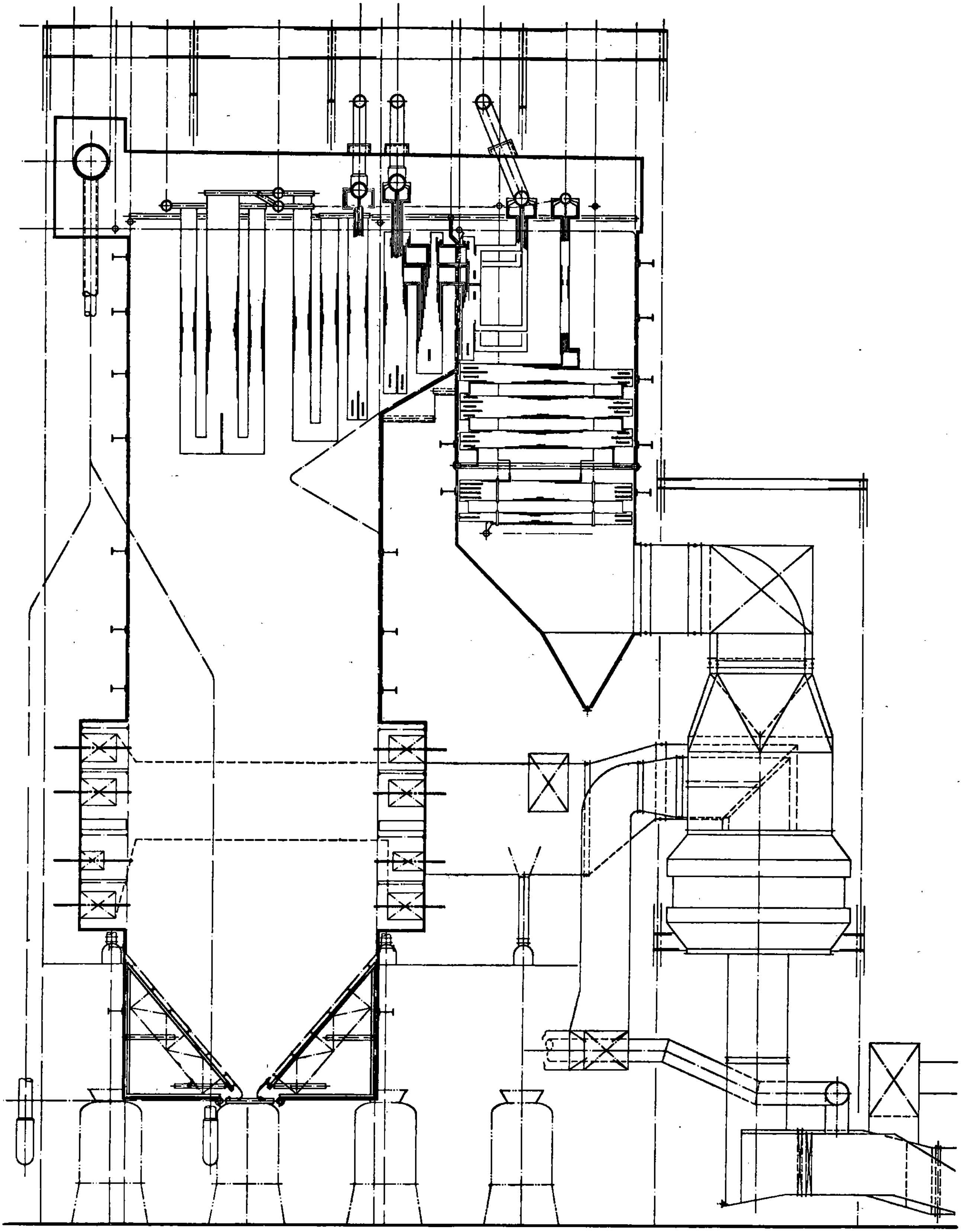

Fig. 13 600 MW pulverized coal fired natural circulation boiler 2825 psig drum operating pressure

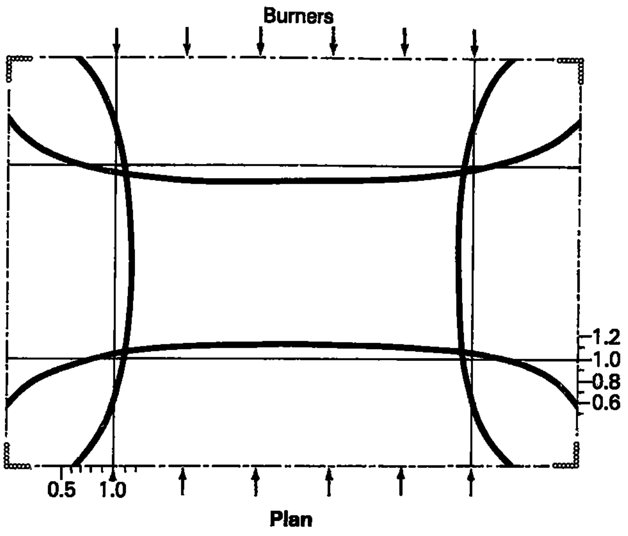

Fig. 14 Inherent horizontal distribution of heat absorption in furnace walls

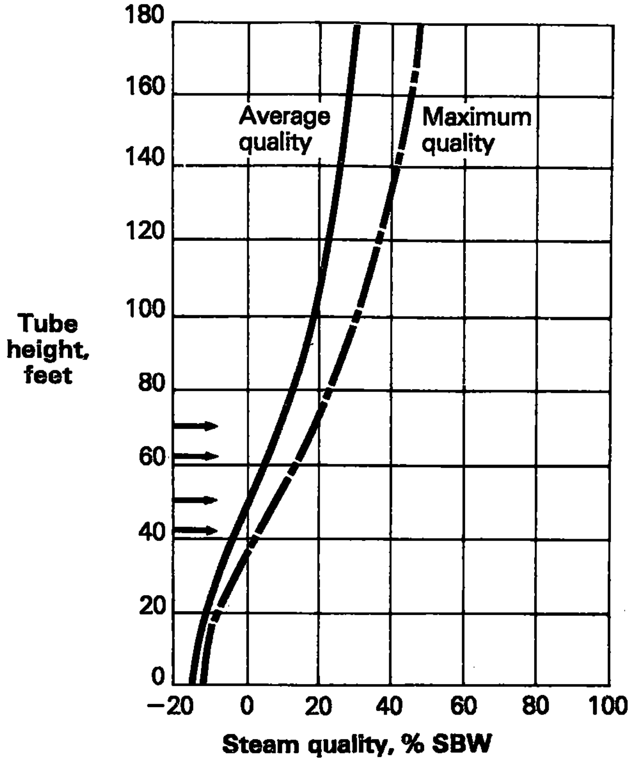

Fig. 15 Steam quality along tubes

by the "quality margin", which is the difference between the expected quality and the maximum allowable (critical) quality. However, as illustrated in Fig. 17, ribbed tubes, even at a mass velocity of only 6 x 10^5 lb/hr-ft^2, provide a much greater quality margin against DNB than smooth tubes, regardless of whether natural or pumped circulation is used. Usually, the average mass velocity in ribbed tube designs is between 7 x 10^5 and 9 x 10^5 lb/hr-ft^2 and, therefore, the actual quality margin (of safety) is higher than that shown in Fig. 17.

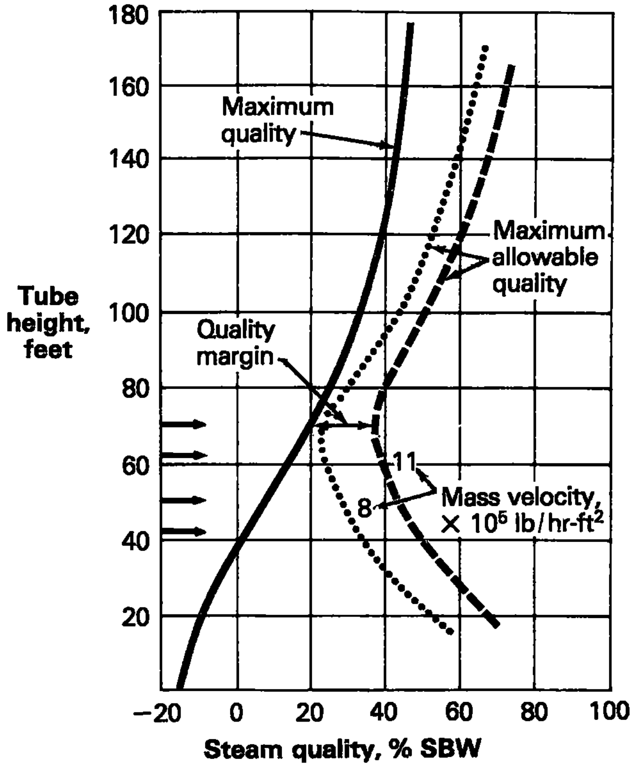

Fig. 16 Margin of safety in smooth membrane wall tubes at 2800 psi

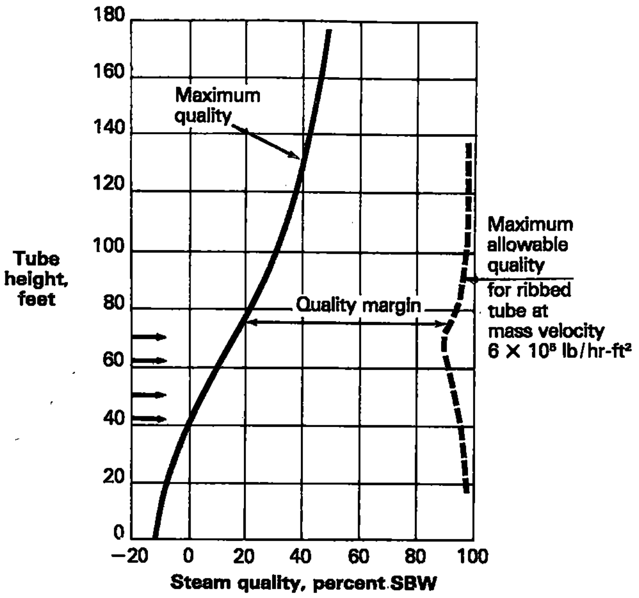

Fig. 17 Margin of safety in ribbed membrane wall tubes

During occasional upsets, such as when an increase in pressure lifts the safety valve(s), the small "pressure margin" (of safety) for prevention of DNB available in smooth tubes may become exhausted, as shown in Fig. 18. Circulating pumps can be utilized to generate higher fluid mass velocities and to provide a somewhat greater pressure margin. However, the large pressure margin inherent in natural circulation designs with ribbed tubes, even at the 3000 psi level, is quite apparent.

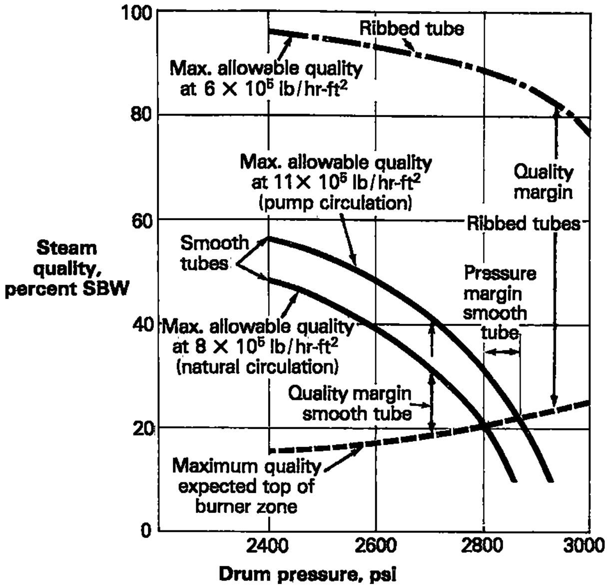

Fig. 18 Effect of pressure on margin of safety at upset absorption rate and minimum mass velocity

RIBBED TUBES PROVIDE A HIGH DNB-RATIO AND FLOW-RATIO

In nuclear power applications, the DNB ratio is a widely accepted criterion for judging the boiling elements from the standpoint of their safety against burnout. By definition:

$$\text{DBN ratio, } R = \text{minimum value of } \frac{\text{DNB heat flux}}{\text{Upset heat flux}}$$

at the design conditions of maximum expected local quality and corresponding minimum mass velocity. This criterion also can be used to assess the margin of safety of furnace designs. It indicates the magnitude of the permissible heat rates to that expected along the tube at the most critical location.

Referring to Fig. 19, the DNB ratio R is equal to the heat flux at points B_1, B_2, B_3, divided by the heat flux at point A. At a mass velocity in furnace tubes of 8 x 10^5 lb/hr-ft², the DNB ratio for smooth tubes is R = 1.05, which is very low. Increasing the mass velocity to 11 x 10^5, which requires a pump, raises the DNB ratio in this example to an acceptable level of R = 1.25. The ribbed tube design, however, has a DNB ratio of R = 2.13, thus providing a considerably greater margin of reserve against high heat absorption rates than possible in smooth tubes, even at very high mass velocities. For comparison, nuclear reactors are designed for a minimum DNB ratio (R) of 1.30.

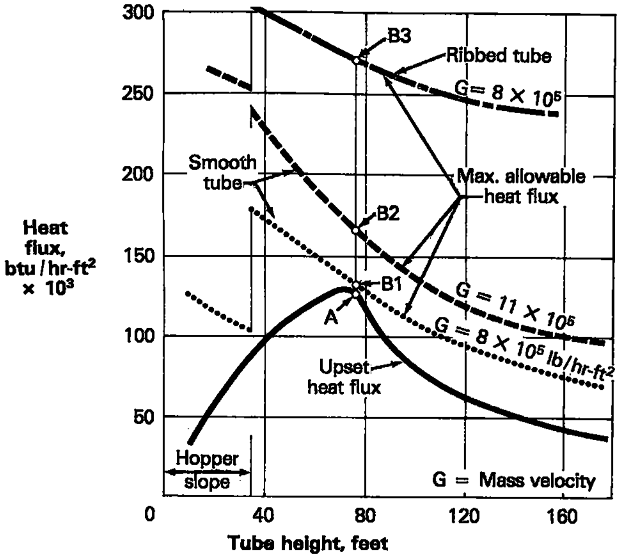

Fig. 19 Maximum heat flux to avoid DNB at maximum quality and minimum mass velocity for 2800 psi.

Similarly, the "flow ratio" provides a measure of the tolerable flow reduction before onset of DNB. By definition the

$$\text{Flow Ratio, } F = \text{minimum value of } \frac{\text{minimum design mass velocity}}{\text{DNB mass velocity}}$$

The DNB mass velocity along the tube (shown in Fig. 20) is determined from the DNB limit data using the operating pressure and the maximum expected local steam quality (from Fig. 15) together with the corresponding upset heat flux (from Fig. 12).

A comparison of the four design margins for the various combinations of the critical parameters that can cause DNB is shown in Fig. 21. It is

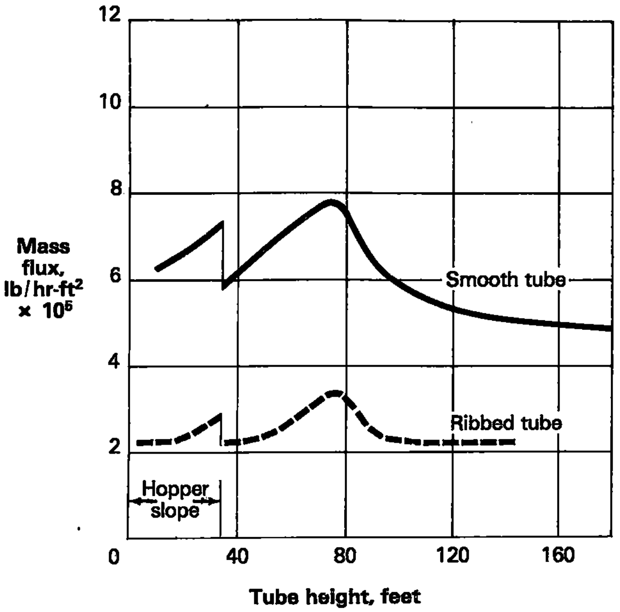

Fig. 20 Minimum mass velocity to avoid DNB at upset heat flux and max. quality for 2800 psi

evident that natural circulation with ribbed tubes can provide more than sufficient mass flow in each tube to avoid the critical combinations that produce DNB in furnace tubes. The degree of safety attainable with the ribbed tube cannot be matched by smooth tubes of any practical design, whether natural or pumped circulation is used.

Tubes	Smooth		Ribbed		Reference figure number
Min. mass velocity × 10^5 lb/hr-ft^2	11	8	8	6	
Type of circulation	Pump	Nat.	Nat.	Nat.	
Quality margin, % point	17	4	69	66	16 17
DNB ratio, R=	1.25	1.05	2.13	1.75	19
Flow ratio, F=	1.41	1.03	2.31	1.76	20
Pressure margin, psi	80	0	>270	>220	18

Fig. 21 Comparison of safety margins. Advantage of ribbed tube over smooth tube at 2800 psi

REDUCED CIRCULATION TESTS(4)

Two series of prolonged tests with reduced circulation were conducted on a 550MW utility boiler to prove the presence of a large margin of safety in the ribbed tube design. The unit is fired with severe slagging coals and operates at a normal drum pressure of 2660 psi with overpressure capability to 2770 psi.

In the first series of tests, lasting nine months, orifice plates were installed in all downcomers to restrict the circulation flow to all circuits by 23 percent. Instrumentation was provided to continuously monitor the important circulation parameters under all operating conditions. The circulation system maintained satisfactory and stable flow conditions even though the boiler experienced transient upsets due to control malfunctions and problems with auxiliary equipment. The water level was stable. The operation at the reduced circulation ratio was exceptionally good.

Based upon the excellent operation, the utility's management permitted the installation of smaller orifice plates in the downcomers which reduced the circulation flow by 35 percent from the original design. The unit, which was originally designed for a circulation ratio of 3.9, has been operating with a circulation ratio of 2.5 (Fig. 22) since December 1976. Operation at the reduced flow has been reliable over the full load range and during all transients. The operation margin available with restricted flow is still greater than that obtainable with smooth tubes.

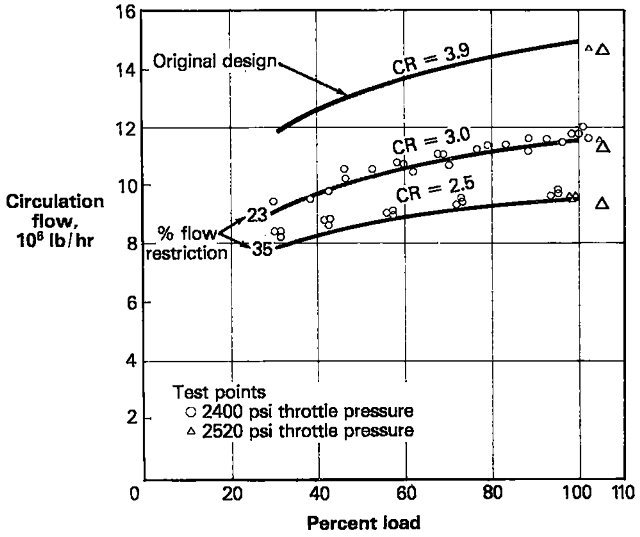

Fig. 22 Reduced circulation tests of a 550 MW, 2400 psi coal fired boiler

NO SIZE LIMIT FOR NATURAL CIRCULATION WITH RIBBED TUBES

Natural circulation boilers with ribbed tubes, even at very high pressures, have no size limitations. Smooth tubes require low qualities, which means a high circulation ratio. The furnace periphery and with it the number of tubes does not increase proportionately with the steam flow. For high circulation ratio, the size of tubes, downcomers, supplies, and risers must be enlarged. There exists an economical limit on the dimensions of the circulatory system which restricts the boiler size.

Since ribbed tubes can tolerate high steam qualities, the potential reduction of circulation ratio with increase in boiler size can be accomplished without affecting the DNB safety margins. Babcock & Wilcox can now build natural circulation boilers with ribbed tubes up to 1300MW in size and 2900 psi drum operating pressure (3050 psi design pressure) that have a high margin of conservatism.

SUMMARY

For high reliability all high pressure drum type boilers must avoid DNB under all operating conditions with a sufficient margin of reserve for upset transients. DNB is a localized phenomenon caused by a critical combination of operation parameters which include pressure, heat flux, steam quality, and mass velocity.

The *overall* circulation ratio often used in the power industry to compare and evaluate the safety of circulation systems is not a pertinent criterion, since it lumps together the flows of the most exposed circuits with those of low duty. Even with high circulation ratios, drum type boilers with smooth tubes may have circuits that operate during upsets close to the combinations of parameters that produce DNB.

The B&W design with ribbed tubes, however, provides high natural circulation flow rates (even at pressures approaching the critical pressure) that maintain significant margins of safety during adverse upsets. Thus, with the use of ribbed tubes, it is possible to meet utility requirements for natural circulation boilers of any size for 2900 psig drum operating pressure, that have high availability and no auxiliary power demand.

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