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Investigation of Free-Forced Convection Flows in Cavity-Type Receivers

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INVESTIGATION OF FREE-FORCED CONVECTION FLOWS IN CAVITY-TYPE RECEIVERS

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submitted to

Sandia National Laboratories

Livermore, California 94550

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1. Problem Review

Free-forced thermal convection losses from cavity-type solar receivers may be a determining factor in establishing their commercial viability. In an early review [1] of the literature it was established that there did not appear to exist, either a useful body of experimental data, or, a theoretical/numerical analysis of the problem, of value for bounding the magnitude and establishing the functional form of these losses.

It has been the purpose of this investigation to bridge part of the gap existing between present knowledge and practical needs. To achieve this the research program has consisted of two parts. The first has as its objective the development of a numerical calculation procedure applicable to cavity-type configurations and flow conditions. The second has as its objective the provision of increased physical insight through flow visualization, and experimental measurements of quantities valuable for the development of the numerical calculation procedure of part one.

The results of the first year of research have already been reported in [1][*]. Those corresponding to year two of research are summarized here.

Although the present investigation has focussed on a configuration which is strongly two-dimensional in the mean flow structure (but turbulent in a truly three-dimensional sense), the extension of the calculation procedure to fully three-dimensional flows is straightforward, albeit laborious.

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[*] The first-year of research was for the period October 1, 1979 to September 30, 1980.

2. Accomplishments

During year two of research, flow visualization experiments were performed for various free-forced convection regimes corresponding to the conditions given in Table 1. Time averaged temperature measurements were made using a specially designed thermocouple rake (composed of 12 thermocouples) in the cavity aperture plane for all flow conditions. In the purely free-convective regime additional measurements were taken in a plane halfway inside the cavity. The apparatus, instrumentation, experimental methodology and an error analysis are described in [1,2].

The total number of temperature profiles corresponding to the tabulated conditions is approximately 70. The flow visualization results corresponding to these conditions have been of considerable value for helping to understand the nature of the cavity flow as a function of experimental conditions. While measurements of the detailed velocity distribution in and about the cavity have not yet been made,* the temperature profile shapes display a strong dependence on the imposed flow conditions. Thus, the temperature profiles provide indirect evidence of the fluid mechanical activity, of additional value for the development and validation of numerical calculation procedures.

Paralleling the experiment, the REBUFFS numerical calculation procedure described in [3] has been developed further to predict forced flow conditions in laminar regime. A selected sample of experimental conditions was computed with the REBUFFS code to establish:

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*It is one of the tasks of year three of research to obtain measurements of mean velocities and turbulence intensities for conditions of free-convection.

1. That large scale trends in the flow visualization results and temperature measurements are qualitatively reproduced by the calculation procedure.

and to quantify:

2. The degree of discrepancy arising between measurements and calculations of temperature, largely attributable to the presence of turbulent diffusion of heat in the experiment.

In addition to the above, a literature review has been completed pertaining to turbulence modeling practices in flows with buoyant effects. The review has shown that the bulk of significant modeling of these flows has been restricted to Boussinesq-approximated equations and high Reynolds number conditions. In the area of chemically reacting (combustion) flows appeal has been made to density-weighted forms of the transport equations, but it renders more difficult the task of modeling several of the correlation terms. Furthermore, comparisons between density-weighted calculations and non-weighted measurements introduce potential sources of inaccuracy in model validation.

2.1 Discussion of Some Experimental Results

Figure 1 shows a set of average temperature profiles typical of the measurements obtained in the cavity aperture plane. The variable parameter in this set is the Reynolds number (or Re^2/Gr). The profiles show clearly a marked dependence on the externally imposed flow. Especially noteworthy is the appearance of a bulging in the profiles for

$0.29 \lesssim Re^2/Gr \lesssim 2.86$. This bulging is a quantitative reflection of a qualitative observation made using the shadowgraph technique. Shadowgraphs showed that for $Re^2/Gr \gtrsim 0.2$ the far field flow approaching the cavity was strong enough to overcome and redirect downwards along the aperture plane some of the hot air emerging from the top of the cavity when it was inclined facing downwards 20° or 45°. For values of $0.25 \lesssim Re^2/Gr \lesssim 1.0$ flow visualization showed that a hot air "bubble" would hover unstably in front of the aperture plane. The size, position and circulation of the bubble were sensitive to fluctuations in the flow induced by buoyancy, and possibly by eddy shedding from the apparatus itself. These results suggest, and preliminary laminar flow calculations given in Fig. 3 appear to confirm, that the development of a hot-air "curtain" in front of an inclined cavity can reduce thermal convective losses for $Re^2/Gr \simeq 1.0$.

The large quantity of experimental information collected during the period of research corresponding to this report precludes its inclusion here. It has been tabulated and plotted and will be fully included in the Ph.D. thesis of K.S. Chen. Currently, a paper describing the study and summarizing all the experimental results is in preparation. It will be submitted for journal review and publication about June 1982 at which time a copy will be submitted to Sandia National Laboratories.

2.2 Discussion of Some Numerical Calculations

A comparison between selected temperature measurements and corresponding numerical calculations is shown in Fig. 2. The calculations were performed assuming laminar flow regime for conditions of the experiment. In general, the qualitative features of the experimental profiles are well reproduced by the calculations although there are some large discrepancies in terms of absolute values. The discrepancies are especially pronounced in regions of the flow (top and bottom walls, and corner regions) where turbulent transport of heat can be expected to be large. Figure 3 shows a plot of the thermal convective loss of a two-dimensional cavity as a function of Re^2/Gr. At a value of about $Re^2/Gr \simeq 1.0$ there is a minimum in the curve fitted through the calculations. The implication of this result is that for conditions of the flow in which buoyancy and inertial forces are in approximate balance, hot air "hovering" about the cavity aperture plane works to reduce thermal convective losses. In principle, cavity receiver designs should be possible in which this effect and its beneficial consequences are exploited.

Although levels of agreement similar to those above have been found between measurements and two-equation (k-ε) turbulence model predictions of aperture plane temperature profiles for $a/b = 1$, $\alpha = 45°$ and $Re^2/Gr = 2.86$, such calculations must be viewed very cautiously. Strictly, this model only applies in regions of the flow where the turbulence Reynolds number is high, and must be expected to fail to predict the flow as $Re^2/Gr \rightarrow 0$ or as α is increased. In particular, strong anisotropy induced by buoyant forces in the flow and its effect on heat transfer cannot be included in the model due to the assumption of an isotropic (scalar) viscosity. A further limitation in the standard high Reynolds k-ε model is the assumption of a forced-flow law of the wall relationship for velocity in the near-wall region. This too, in an incorrect supposition as $Re^2/Gr \rightarrow 0$.

These and related limitations have made it necessary to consider the development of improved turbulence model practices specifically addressing the role of buoyancy in the flow. It is one of the objectives of the third year of research to achieve this in the context of thermally-driven cavity flows.

3. Conclusions

Experimental results from the present two-dimensional investigation and the three-dimensional study being conducted at Sandia National Laboratories, Livermore, strongly support the notion that turbulent transport of heat represents an important contribution to the overall transport taking place through the aperture planes of cavity-type solar receiver geometries. The turbulent transport process is significantly influenced by large fluctuations in body forces which, to date, have not been adequately included in state-of-the-art models of turbulence.

Although laminar and turbulent-regime temperature predictions of selected two-dimensional cavity experiments display encouraging qualitative agreement, an increased accuracy in the calculations requires an improvement of current modeling practices. The measurements and flow visualization results obtained during year two of research will be of great value for achieving such an advancement.

Preliminary results from laminar flow calculations suggest that for $Re^2/Gr = 1$ convective losses from a two-dimensional cavity are reduced to a minimum value due to a protective "curtain" of recirculating hot air. This result must now be confirmed for turbulent flow regime.

4. Plans for Year Three of Research

During the last year of research attention will be focussed on extending the two-equation (k-ε) turbulence model of [5] to flows with strong buoyant effects. Although (to some extent) this has already been done for flows with weak buoyant effects, the results achieved are not sufficiently universal and accurate simultaneously [6-8]. Comparisons will be made between two-dimensional predictions and measurements of selected experimental cases of this investigation. An extrapolation to large scale two-dimensional representations of receiver configurations will also be performed.

The REBUFFS numerical procedure will be extended for predicting three-dimensional laminar flows. It is anticipated that time will allow an extension to the laminar regime only.

Pointwise measurements of velocity and turbulence intensity will be made in the experimental apparatus of this study for conditions of pure free-convection using a laser-Doppler velocimeter. These new results will further broaden the experimental data base required for developing, testing and applying new modeling concepts of value for predicting convection losses from heated cavity-type configurations.

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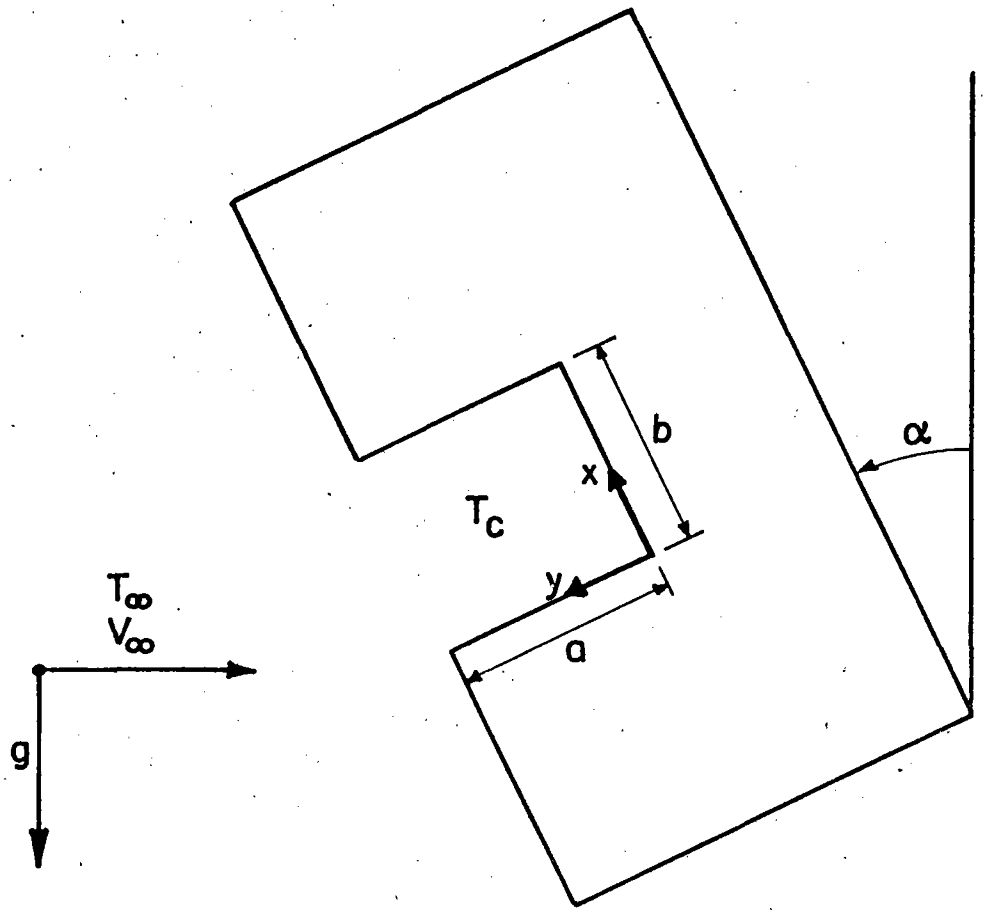

Table 1. Definition of experimental configuration and flow conditions for which visualization and mean temperature profiles have been measured.

DEFINITIONS

$Re = b\ V_\infty / \nu_f$

$Gr = g\ b^3 (T_c - T_\infty) / T_\infty \nu_f^2$

$\theta = (T_c - T_\infty) / T_\infty$

$T_f = (T_c + T_\infty) / 2$

EXPERIMENTS PERFORMED FOR THE FOLLOWING CONDITIONS

$\theta = 1.26$ (smaller values visualized also)

$Gr = 5.3 \times 10^6$

Re = 0, 192, 430, 1240, 1890, 2710, 3950

V_∞ = 0, 0.07, 0.16, 0.45, 0.69, 0.99, 1.41 (m/s)

a/b= 0.5, 1.0, 1.46 and $\alpha = 0^o, 20^o, 45^o$

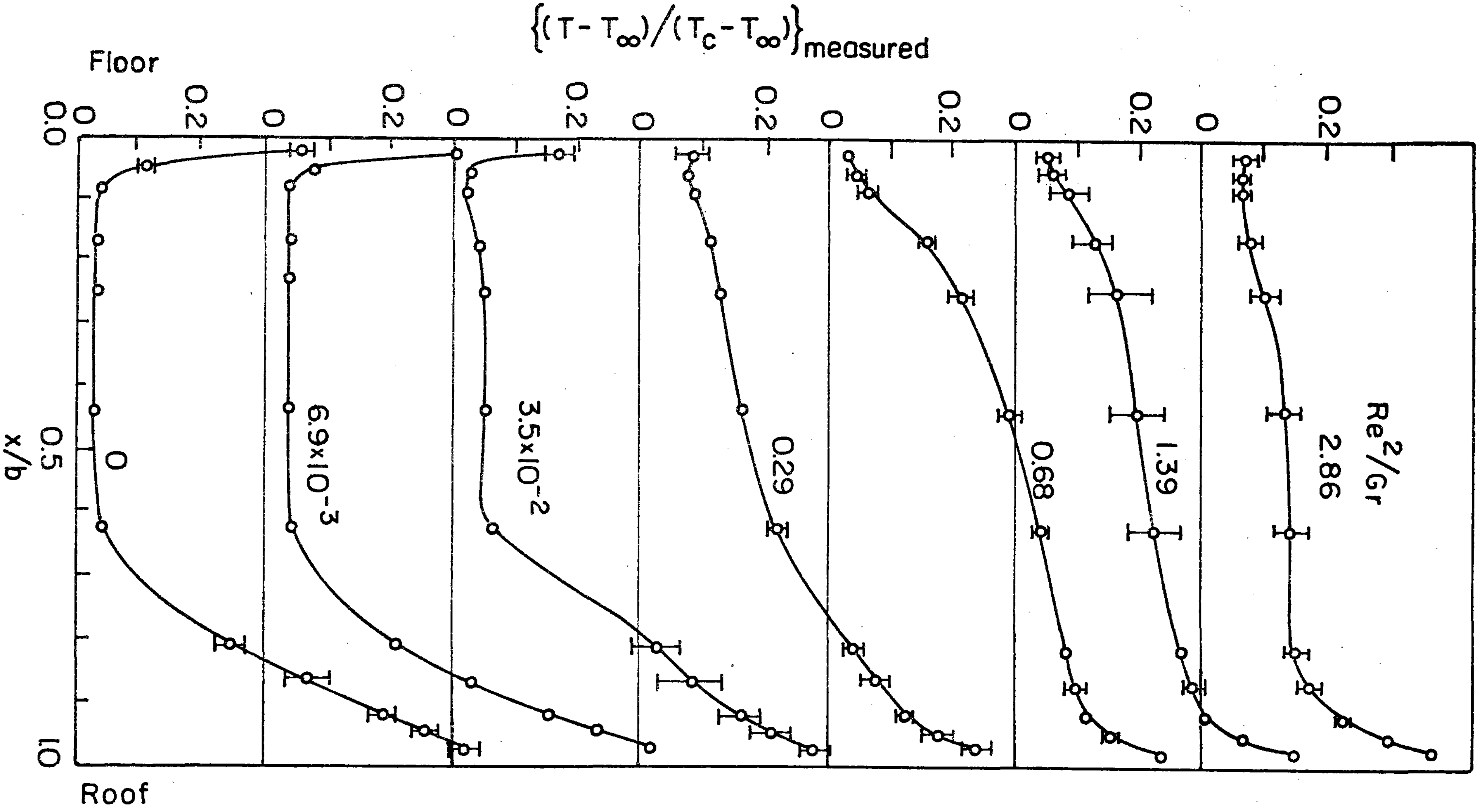

Figure 1. Aperture plane temperature profiles: $a/b = 1.0$, $\alpha = 45^0$, $T_\infty = 294$ K, $Gr \simeq 5.3 \times 10^6$, $(T_c - T_\infty) / T_\infty \simeq 1.26$.

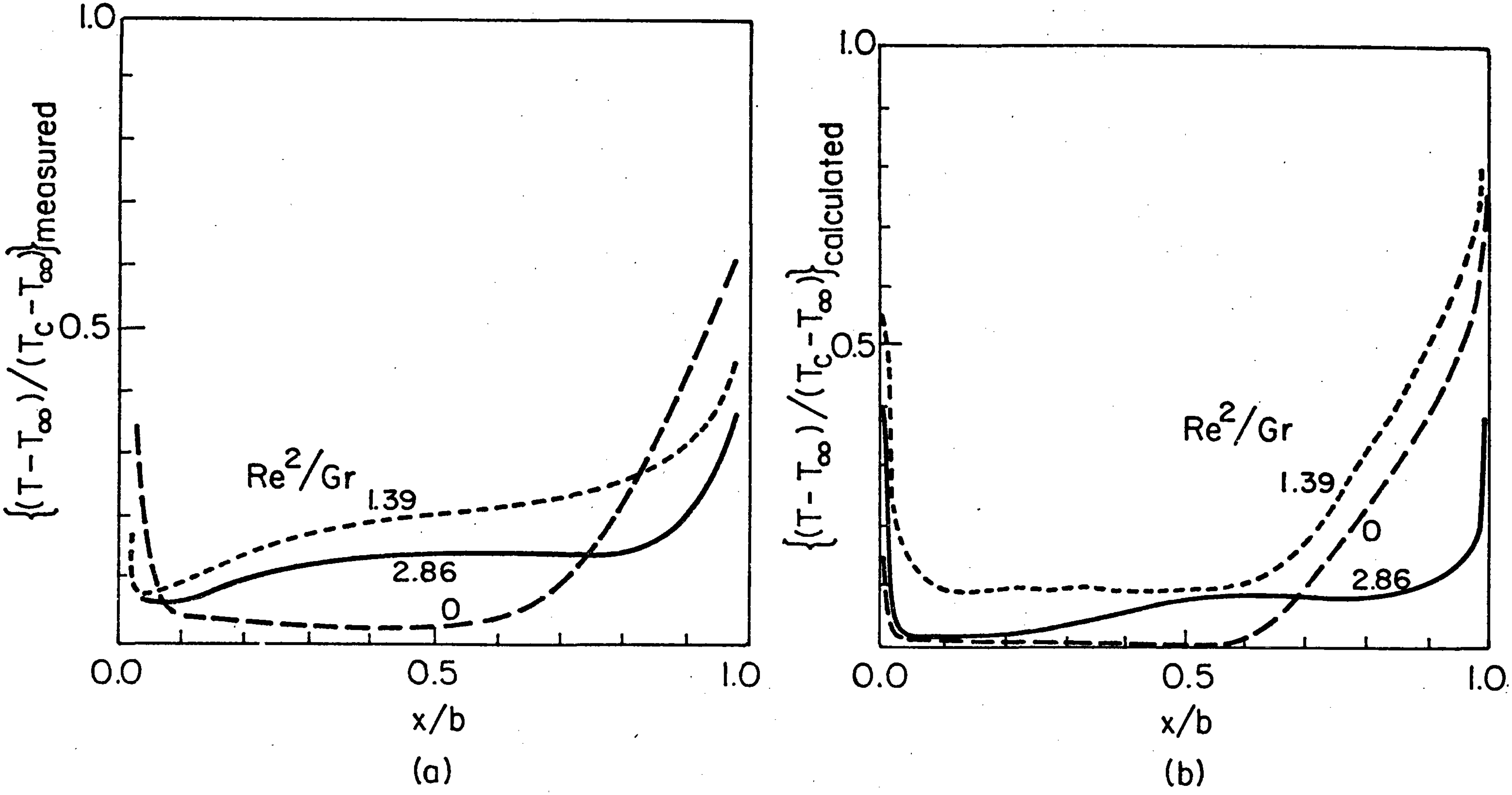

Figure 2. Comparison between measured and calculated (laminar regime) aperture plane temperature profiles for conditions of Figure 1.

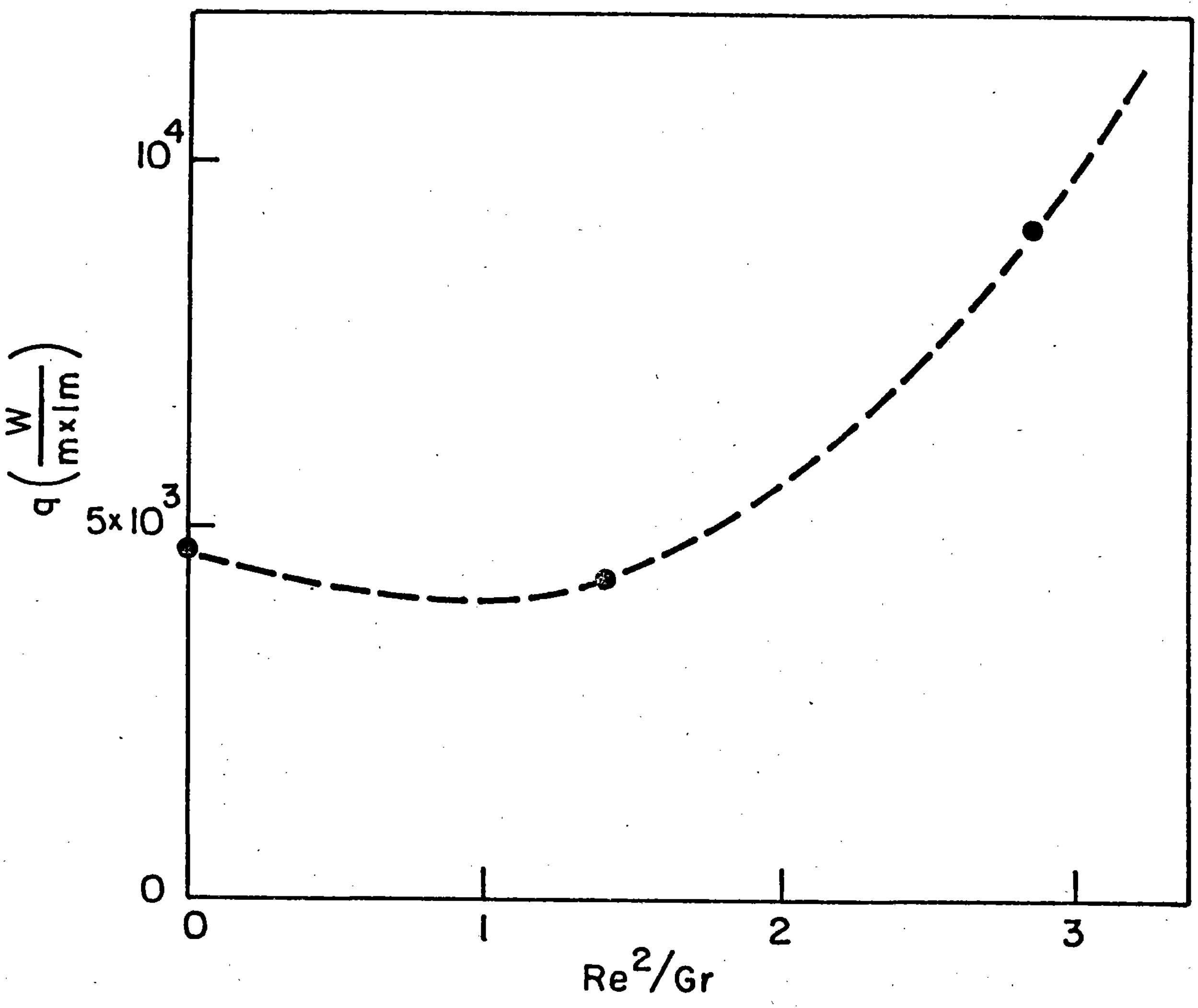

Figure 3. Thermal convective flux from a 2-D cavity as a function of Reynolds number for conditions of Figure 1. Dashed line fitted through calculated points.

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