A detailed comparison of the present data with the distributions of temperature and velocity predicted by Bayley [9] is not given because of the close similarity between that work and the work of Eckert and Jackson [2]; it suffices to say that agreement is even less satisfactory than with the predictions of those authors. This result is not surprising in view of the trends in the heat transfer data.

Conclusions

New experimental measurements of temperature profiles, velocity profiles, and local heat transfer rates in natural convection on a vertical plate surface have been presented. For the important turbulent region, these have been shown to be in reasonable agreement with the only existing experimental results. The heat transfer data are also in agreement with theoretical predictions, but this is not the case with regard to the temperature and velocity profiles.

For the laminar part of the boundary layer, the results are in good agreement with existing theory, thus giving some indication of the accuracy of the experimental techniques.

No previous data exist for the transition region, and the present results show important details of the transition process in terms of the development of profiles of mean properties.

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References


DISCUSSION

Dr. Charles Y. Warner

Dr. Cheesewright is to be congratulated on a fine work, particularly with regard to the measurement of velocities within the turbulent natural convection layer.

As often happens, a very similar work was being conducted contemporaneously [14, 15]. It is hoped that a brief comparison of the results will be helpful.

With regard to the measured temperatures, the results of the two researches show a reassuring similarity. Fig. 10 shows some of the temperature data reported in [14], with one set of Dr. Cheesewright’s data superposed. Although some error was likely introduced by the scaling of the latter data from Dr. Cheesewright’s Fig. 6, the agreement is very good.

On the other hand, there is a significant disagreement in the heat transfer results. The research by Dr. Cheesewright appears to support the Eckert [2] theory, while measurements reported in references [14, 15] give substantial credence to the Bayley [9] theory and the Saunders’ [16] measurements. Fig. 11 shows some of the average heat transfer results taken from [14], where recent direct measurements are compared to those of earlier researchers [1, 16], and the analytical results of Eckert and Jackson [2] and Bayley [9]. As may be seen, these recent measurements give support to the Bayley correlation.

A comparison of the analytical techniques of Bayley and of Eckert and Jackson shows that a good deal more care has been taken in references [14, 15]. The research by Dr. Cheesewright appears to be a very fine work, particularly with regard to the measurement of velocities within the turbulent natural convection layer.
exercised by the former author in the selection of an approximate temperature profile. The integral method of solution, common to both works, depends to a certain degree upon the choice of a proper temperature profile. As Dr. Cheesewright has pointed out, in the light of recent measurements the \( \frac{1}{2} \)-power profile, as used by Eckert and Jackson, is not an appropriate profile for this case.

The disagreement in the two recent experimental studies should be resolved. Perhaps a short comparison will serve to do this. In Fig. 3, Dr. Cheesewright shows measured local heat transfer results, including some which may have been subject to "trailing edge effects." It should be noted that in the absence of these points the trend of the reported data is somewhat less conclusively analogous to that of the Eckert theory. Further, an examination of the methods used for heat-flux measurement shows that the Cheesewright results depended upon measurement of the near-wall gradient of temperature, corrected for thermal-conductivity temperature dependence. The Warner result, on the other hand, was based on direct measurement of temperature taken by Warner nearer the plate surface than those reported by the author, show a definite trend toward milder gradient, and thus lower heat flux near the wall.

Also, although Cheesewright mentions that the surface temperature in his apparatus was adjustable for uniformity, he chose to extrapolate for about 0.02 in. through a large temperature gradient to find it, while no direct measurement is reported. Thus, some tendency might be expected toward higher heat-flux rates from his results than those reported by Warner.

It can be shown from dimensional considerations and analogy with the forced-convection case that the Nusselt number might reasonably be expected to vary directly as the square root of the Grashof number as the latter approaches infinity. Further experimental work is needed to substantiate such a trend, if it indeed exists. Until such evidence is accumulated, the analytical result of Bayley is at least as well verified experimentally as that of Eckert [2]. Because of the additional consideration given therein to the selection of profiles, it is perhaps also superior on analytical grounds.

**Nomenclature**

\[ \text{Nu} = \text{average Nusselt number over distance } x \]

\[ \text{Ra} = \text{average Rayleigh number over distance } x \]

**Additional References**


Author’s Closure

The author would like to thank Dr. Warner for his interesting discussion.

While the agreement between Dr. Warner’s data and that in the paper is satisfactory in respect to the general nature of the turbulent temperature profiles, the data presented by Dr. Warner in Fig. 12 is disturbing. The trend indicated in Fig. 12 and remarked upon by Dr. Warner, of a moderation of the temperature gradient very close to the wall, is sufficiently unusual to merit detailed consideration. The drawing up of an energy account for a region extending from the wall out to 0.03 in., based on the data in Fig. 12 and velocity data from Fig. 8, leads one inescapably to the conclusion that in the vicinity of 0.03 in. from the wall, the contribution of the turbulent transport to the heat transfer perpendicularly away from the wall is negative. Such a result is sufficiently out of keeping with existing data on turbulent boundary layers to suggest that it should be treated with extreme caution.

In the event that the data in Fig. 12 does not represent a true picture of the turbulent boundary layer, two possible explanations come to mind. One is that the “wall effect” was larger than suspected, and it was indeed this problem which deterred the author from making measurements closer than 0.05 cm from the wall. The other and possibly more likely reason is suggested by the fact that there is no indication in reference [14] of any method being used to obtain the true mean value of the local fluctuating temperature, other than averaging “by eye.” A study of the turbulent temperature fluctuations as given in reference [3] suggests that averaging “by eye,” as compared to the counting technique used in this work, could give rise to an error sufficient to cause the inflection point in the temperature profile shown in Fig. 12.

With the foregoing considerations in mind another explanation must be sought for the apparent discrepancy in the heat-transfer data. The author feels that the discrepancy is most probably attributable to the fact that the heat-transfer data reported in this paper are truly local while those determined by Dr. Warner are averaged over a significant length of plate. This is particularly noticeable when Dr. Warner’s data for Grashof numbers in the transition region [14] are compared with the data in Fig. 2. The “step” in the data in Fig. 2 is almost entirely smoothed out by the averaging involved in Dr. Warner’s measurements. The arrangement of the present experiment did not permit the measurement of overall heat-transfer data from the plate, so that the present data cannot easily be compared with that given by Dr. Warner in Fig. 11.

In conclusion it must be stated that the present work suggests that neither the work of Eckert and Jackson [2] nor that of Bayley [9] provides a wholly satisfactory description of turbulent natural convection boundary layer and that more theoretical work in this field is needed, together with an extension of the experimental work to higher Grashof numbers.