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LOW RAYLEIGH NUMBER NATURAL CONVECTION HEAT TRANSFER FROM HIGH-TEMPERATURE HORIZONTAL WIRES TO GASES

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INTRODUCTION

THE WIDELY used McAdams correlation [1] for low Rayleigh number natural convection heat transfer from horizontal cylinders is based on experiments which, in the main, were limited to moderate temperature differences. For high temperature wires in gases, the only contributions to the McAdams correlation are the data of Petavel [2] and of Langmuir [3], which date respectively from 1901 and 1912. In the present paper, new high temperature data are reported for gases and, in addition, the data of [2, 3] are re-evaluated using presently available thermophysical properties. The McAdams correlation and that of Mikheyev [4] are re-examined in light of the new and the re-evaluated data. In addition, the effect of calculating the thermal expansion coefficient as $1/T_\infty$ (T_∞ = gas ambient temperature) instead of at the film temperature is investigated.

EXPERIMENTAL APPARATUS

The present experiments were performed at both elevated and atmospheric pressures, as well as at high temperature. Correspondingly, a pressure vessel was used as the test chamber. The vessel itself was a horizontal cylinder, 165 mm in diameter and 110 mm long. Within the vessel, a 0·4-mm dia. platinum wire was mounted along a horizontal diameter, midway between the end faces of the vessel.

Heating was accomplished by passing d.c. current from a battery through the wire. The overall heated length of the wire was 110 mm. To avoid end effects, two voltage taps were spot welded 60 mm apart, thereby enabling measurement of the voltage drop in the central portion of the wire. The 60-mm long segment of wire served as the test section. The wire itself was of the highest purity platinum obtainable.

The pressure vessel was fully immersed in a circulating, thermostatically controlled water bath in order to maintain temperature uniformity within the vessel.

The temperature of the test section was determined by measuring its electrical resistance. In this connection, the resistance at 0°C was measured prior to the tests with a Mueller bridge. This information was then employed in conjunction with the well-established relation for the relative change of resistance with temperature for pure platinum [5]. The temperature of the gas in the chamber was measured by a calibrated copper–constantan thermocouple situated about 20 mm below the test section.

Experiments were performed using either helium or argon as the heat transfer medium in the test chamber,† respectively at pressures of 1 and 7·5 atm and 1, 7·5 and 10 atm. At each pressure level, measurements were made at 7–15 wire temperature levels ranging up to approximately 900°C. The gas temperatures were generally in the range from 20–25°C.

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†Neither of these gases had been employed in [2, 3].

RESULTS AND DISCUSSION

As a necessary first step in the computation of convective heat-transfer coefficients, the measured values of ohmic heating in the test section were corrected for radiative losses from the surface of the wire. In this connection, values of the emittance of platinum wire were taken from the comprehensive compilation of Gubareff and co-workers [6]. For the temperature range of the present experiments, the normal emittance data were well correlated by a straight line passing through the points $\varepsilon_n = 0{\cdot}059$, $T = 500$°K and $\varepsilon_n = 0{\cdot}13$, $T = 1000$°K. The hemispherical emittances ε used in the calculations were evaluated from $\varepsilon = 1{\cdot}2\,\varepsilon_n$.

The radiation corrections in the case of helium were very small, with the extreme being 5 per cent. For argon, there were more substantial corrections (10–20 per cent) at higher wire temperatures and lower gas pressures.

Corrections to the ohmic heating were also made to account for test section heat losses owing to conduction along the voltage taps. These corrections were calculated using the well-established relationships of fin theory.

With the convective heat-transfer rate q determined by subtracting the radiation and conduction losses from the ohmic heating, the results were cast into dimensionless form by using the definitions

$$h = \frac{q}{T_w - T_\infty}, \qquad Nu = \frac{hD}{k},$$
$$Gr = \frac{g\beta\rho^2(T_w - T_\infty)D^3}{\mu^2}, \qquad Pr = \frac{c_p\mu}{k}. \qquad (1)$$

In order to facilitate comparison with the correlations of McAdams and Mikheyev, the thermophysical properties appearing in the foregoing equations were evaluated at the film temperature $T_f = (T_\infty + T_w)/2$. In particular, the expansion coefficient β was evaluated as $1/T_f$. Later, the effect of taking $\beta = 1/T_\infty$, as suggested by boundary-layer theory, will be examined. The argon properties needed for equation (1) were taken from [7], whereas for helium, the density and specific heat, viscosity, and thermal conductivity were respectively from [8–10].

The Nusselt number results thus obtained are plotted in Fig. 1 as a function of the Grashof–Prandtl product (i.e. the Rayleigh number). The data cover the range of $GrPr$ from 2×10^{-3} to 40. Also included in the figure are data from the experiments of Petavel [2] and Langmuir [3]. Before plotting these data, radiation corrections were applied to

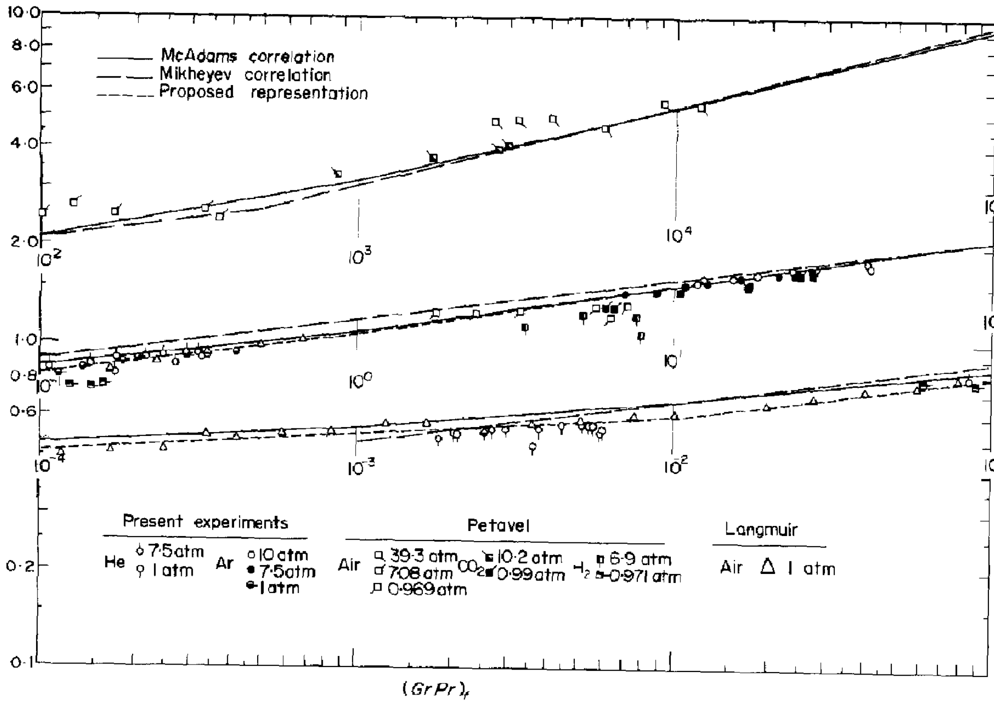

FIG. 1. Nusselt number results with properties evaluated at the film temperature.

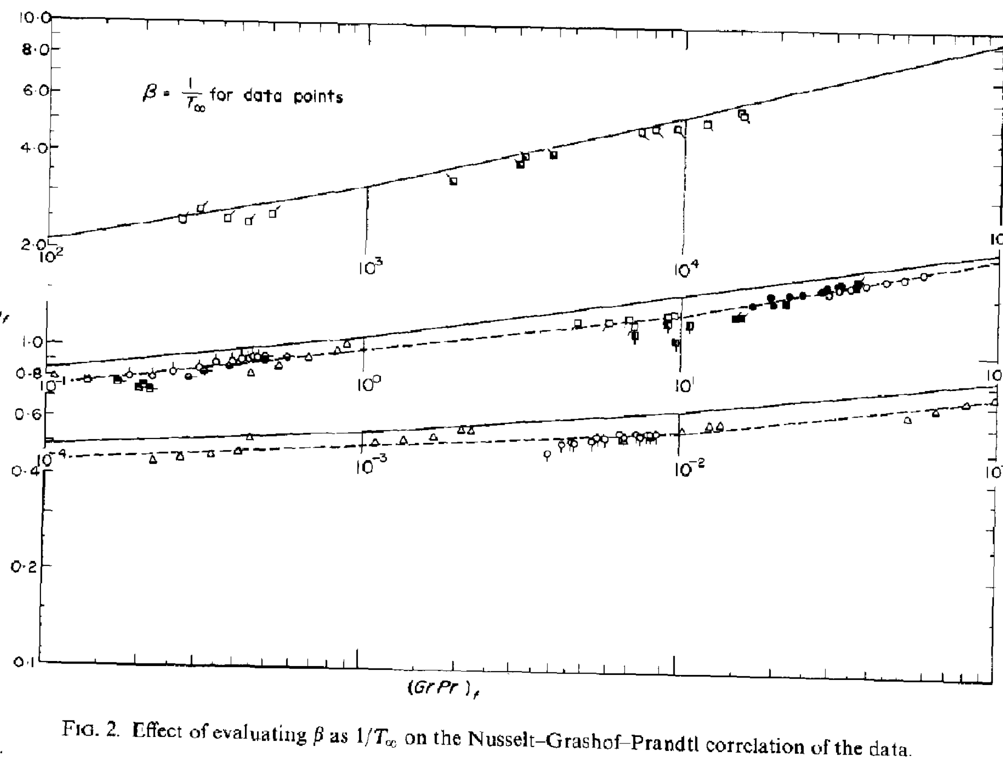

FIG. 2. Effect of evaluating β as $1/T_\infty$ on the Nusselt–Grashof–Prandtl correlation of the data.

them using the same radiation properties as were employed in correcting the present data. The results of all three investigations cover a nine-decade range of the Rayleigh number. To accommodate this range, three abscissa ranges, each covering three decades, are employed in the figure. The solid and long-dashed lines respectively represent the correlations of McAdams [1] and Mikheyev [4].

Examination of the figure indicates that both the present data and that of Langmuir generally fall within 10 per cent of the McAdams correlation, with a clear tendency for the data to lie below the correlating line. Whereas Petavel's data appear to scatter more than the others, it also lies below the correlation in the range of $GrPr$ that is common to all three sets of data.

In light of these observations, the McAdams correlation appears to be generally adequate for predicting low Rayleigh number natural convection from high temperature wires to gases. On the other hand, a better representation may be obtained by correlating on the basis of the present data and that of Langmuir. Such a correlation is represented by the short-dashed lines, the coordinates of which are given in Table 1.

Table 1. Coordinates of proposed correlations

$GrPr$	Nu (Fig. 1)	Nu (Fig. 2)
10^{-4}	0·463	0·439
10^{-3}	0·525	0·499
10^{-2}	0·596	0·565
10^{-1}	0·800	0·745
10^{0}	1·07	0·985
10^{1}	1·51	1·31
10^{2}	2·11	2·00

Except in the range of $GrPr$ between 10^{-3} and 10^{-2}, the data appear to favor the McAdams correlation over the Mikeyev correlation.

For natural convection boundary layers, the assumption of pressure invariance across the boundary layer leads to $\beta = 1/T_\infty$ for a perfect gas. The effect of evaluating β in this way will now be examined. For this purpose, the data were reduced using the groupings defined by equation (1), with all fluid properties evaluated at the film temperature T_f but with β equal to $1/T_\infty$.

The thus-evaluated data are shown in Fig. 2, where the McAdams correlation is also indicated. The effect of the re-evaluation of β is to shift the data to the right relative to the McAdams line, thereby widening the gap in the range covered by the present data and that of Langmuir. Therefore, if it is desired to evaluate β as $1/T_\infty$, then the McAdams correlation no longer suffices. A proposed correlation of the data is indicated by the short-dashed line in Fig. 2, and the corresponding coordinates are listed in Table 1.

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TRANSIENT CONDENSATION WITHOUT CONDENSATE FLOW

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NOMENCLATURE

- c, specific heat;
- h, heat-transfer coefficient;
- h_{fg}, latent heat of vaporization;
- k, thermal conductivity;
- t, time;
- T, temperature;
- α, thermal diffusivity;
- δ, condensate (liquid) layer thickness;
- λ, defined by equation (3) or (5);
- ρ, liquid density.

Subscripts

- l, liquid;

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