

# AN EXPERIMENTAL INVESTIGATION OF FREE CONVECTION HEAT TRANSFER IN SUPERCRITICAL HELIUM

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**Abstract** – An experimental study of free convection heat transfer from a copper sphere to supercritical helium is presented. The heat-transfer coefficient is measured in the transposed critical line region covering pressures from 2.3–35 atm (0.23–3.55 MPa) and temperatures from 5.3 to 25 K. Empirical correlations accurate to  $\pm 20\%$  between  $Nu$ ,  $Pr$ ,  $Gr$ ,  $\rho_b$ ,  $\Delta\rho$ ,  $T_b$  and  $\Delta T$  are obtained. A boiling-like phenomenon is observed experimentally near the critical point in that the heat-transfer coefficient  $h$  increases with temperature difference  $\Delta T$  until  $h$  reaches a maximum after which  $h$  decreases for larger  $\Delta T$ .

## NOMENCLATURE

|              |   |
|--------------|---|
| $a$ ,        | constant;                                       |
| $a_n$ ,      | polynomial coefficient;                         |
| $b$ ,        | constant;                                       |
| $c$ ,        | constant;                                       |
| $C$ ,        | constant;                                       |
| $C_p$ ,      | specific heat at constant pressure;             |
| $d$ ,        | constant;                                       |
| $D$ ,        | sphere diameter;                                |
| $e$ ,        | constant;                                       |
| $g$ ,        | gravitational acceleration;                     |
| $Gr$ ,       | Grashof number $= g\beta(T_w - T_b)D^3/\nu^2$ ; |
| $h$ ,        | heat-transfer coefficient;                      |
| $k$ ,        | thermal conductivity of helium;                 |
| $n$ ,        | an integer;                                     |
| $Nu$ ,       | Nusselt number $hD/k$ ;                         |
| $Pr$ ,       | Prandtl number $= C_p\mu/k$ ;                   |
| $R$ ,        | resistance;                                     |
| $Re$ ,       | Reynolds number;                                |
| $T$ ,        | thermometer temperature;                        |
| $T_b$ ,      | helium temperature;                             |
| $T_{pr}$ ,   | temperature on the transposed critical line;    |
| $T_w$ ,      | surface temperature of the sphere;              |
| $\Delta T$ , | temperature difference.                         |

## Greek symbols

|                |   |
|----------------|---|
| $\beta$ ,      | coefficient of thermal expansion;         |
| $\delta$ ,     | boundary layer thickness;                 |
| $\mu$ ,        | viscosity;                                |
| $\nu$ ,        | kinematic viscosity;                      |
| $\rho$ ,       | density;                                  |
| $\rho_b$ ,     | density of helium at bulk temperature;    |
| $\rho_w$ ,     | density of helium at surface temperature; |
| $\Delta\rho$ , | $\Delta\rho = \rho_b - \rho_w$ .          |

## INTRODUCTION

FREE convection heat-transfer studies were among the first in which the heat-transfer properties of supercritical fluids were demonstrated. Schmidt [1] found that the free convective heat transfer to supercritical ammonia and  $\text{CO}_2$  for a closed vertical pipe was larger than through copper by a factor of several thousand. Supercritical effects are attributed to the abnormally large values of the expansion coefficient and the specific heat, and the relatively low viscosity of fluids near the critical point. Thus a large Grashof number can be achieved in a relatively small system with a small temperature difference. With forced circulation free convection can still be the predominant heat-transfer mechanism for  $Gr/Re^2 \geq 1$  [2]. For Reynolds numbers of  $10^5$  such conditions can be easily reached with supercritical helium because of the large thermal expansivities and the small kinematic viscosities encountered. For large conduits and low flow rates the heat transfer will be mainly by free convection while forced convection will predominate for small conduits at high flow rates.

Both free and forced convection heat-transfer data are needed. Several experiments on forced convection heat transfer to supercritical helium have been reported [3–7] but only a few free convection heat-transfer studies have been made. Klipping and Kuzner [8] studied free convection heat transfer from horizontal cylinder for conditions of uniform heat flux. Sato [9] studied free convection heat transfer from vertical cylinders in a limited range of temperatures. Irie *et al.* [10] studied free convection heat transfer in supercritical helium near the critical point in the temperature

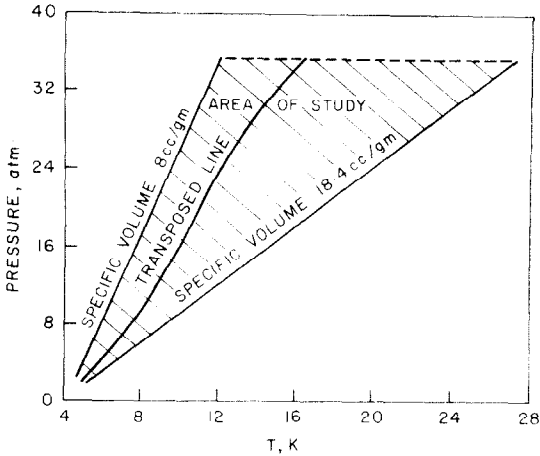


FIG. 1. Area of study shown on the pressure-temperature diagram.

range of 4.5–6 K and in the pressure range of 2–4.3 atm.

Preliminary brief results of this experimental study of free convection heat transfer from a copper sphere to supercritical helium were reported at the 1976 ICEC Conference [11]. The heat-transfer coefficient is determined in the vicinity of the transposed critical line within the range in  $T, P$  space shown in Fig. 1, covering pressures from 2.3 to 35 atm and temperatures from 5.3 to 25 K. The sphere is suspended inside a thick wall cylinder partially filled with liquid helium. First the helium is heated to the desired temperature and pressure. Next the sphere is heated with a constant power heater for a short time to establish steady state conditions. Then the temperature differences between the sphere and helium are measured. The helium volume inside the cylinder is large enough so that no heated helium circulates back to the sphere during the short duration steady state heat-transfer measurements. This technique has the following advantages: (i) the method of adjusting helium temperature is greatly simplified, (ii) convection currents other than currents induced by the experiment are eliminated. The present experimental study covers a wide range in  $P, T$ , and  $\Delta T$  phase space for the uniform temperature case. The measured heat-transfer coefficients seem reasonably consistent with the other experimental studies of different geometries by Klipping and Kuzner [8], Sato [9] and Irie *et al.* [10] as well as with the analytical study of laminar free convection heat transfer by Hilal [12]. The main difference is that our experiments, which cover the widest range in  $P, T$  phase space, indicate that a boiling-like phenomenon takes place near the critical point. Further details of this study can be found in reference [13].

This experimental heat-transfer study in supercritical helium may be useful in understanding free convection heat transfer of other fluids in the supercritical region. To that end the Nusselt number is correlated to Grashof and Prandtl numbers as well as to the

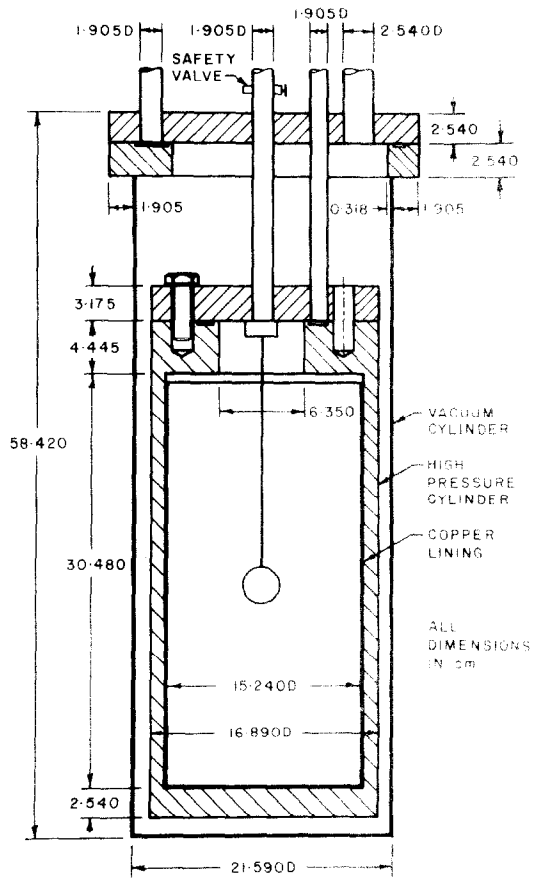


FIG. 2. Experimental apparatus.

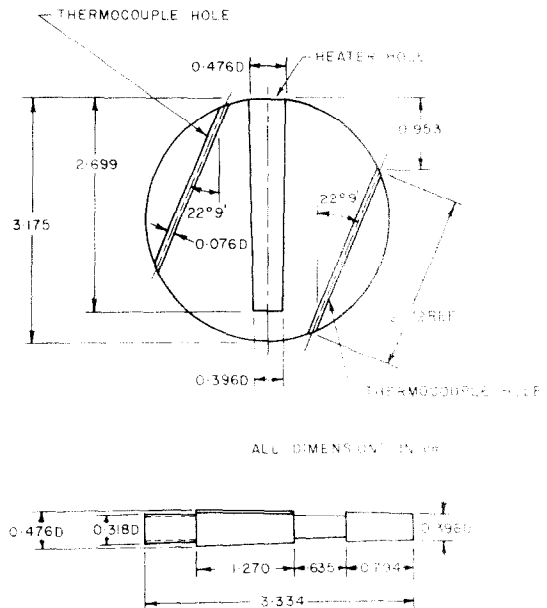


FIG. 3. The copper sphere and its heater.

temperature and density differences. The best correlations are obtained when the properties are evaluated at the bulk helium temperature.

#### EXPERIMENTAL APPARATUS

A schematic of the apparatus is shown in Fig. 2. A copper sphere is suspended on a nylon rod in helium contained in a high pressure cylinder. The high pressure cylinder is surrounded by a larger cylinder immersed in a liquid helium bath which is evacuated to minimize heat losses from the pressure cylinder to the helium bath. A sphere is chosen because a spherical heat-transfer surface is universal in that heat transfer does not depend on geometrical aspect ratios. The sphere is certified OFHC copper and is 3.175 cm in diameter. As seen in Fig. 3 the sphere has two holes for thermocouples and a conical hole for the pulsed 850  $\Omega$  heater. The thermocouple junctions are mounted flush with the external surface to measure temperatures at the top and bottom of the sphere which, it is found, are identical to within the experimental accuracy of 0.05 K. Thermocouple lead corrections are minimized since 2 cm of leads pass through and are in thermal contact with the sphere. The nylon rod causes a heat loss of 0.4% of the power input to the sphere.

The high pressure cylinder is sealed with double O-rings of the self energized type. This combination is adequate to maintain the surrounding vacuum at less than 0.1  $\mu\text{m}$  for internal pressures up to 35 atm. By maintaining the vacuum between the two O-rings at 20  $\mu\text{m}$  the leakage is reduced to  $10^{-4}$  of what it would be for one O-ring. The assembly in Fig. 2 is submerged in 4.2 K liquid helium so that the external surface of the vacuum cylinder is at 4.2 K. The estimated heat leak through the vacuum section surrounding the experimental cylinder is only 0.65 W. Thus the maximum cooling rate of the 70 kg pressure cylinder and the 500 g of helium enclosed is limited to  $10^{-4}$  K/s and the temperature drift is only 3 mK during a 30 s experiment. The inner lining of the high pressure cylinder is copper to maintain a uniform helium temperature and prevent stratification from taking place. The diameter of the pressure cylinder is large compared to the estimated boundary layer thickness,  $\delta/D = 0.001$ ; therefore the sphere is considered to be suspended in an infinite medium.

#### MEASUREMENTS

The quantities measured in the experiment are the helium temperature and pressure in the high pressure container, the temperature difference between the surface of the sphere and the surrounding helium, and the power input to the heater in the sphere. Pressures are measured by two pressure gauges supplied by Mantehson Gas Products Co., one is used up to 7 atm, and the other can be used up to 140 atm. The specified accuracy of each gauge is 0.5%.

The helium temperatures are measured by two carbon resistance thermometers which are calibrated

using a calibrated germanium thermometer. One of the thermometers is mounted on the nylon rod above the sphere and the other below the sphere near the bottom of the pressure cylinder. The carbon resistance is fitted to an expression of the form

$$\frac{1}{T} = \sum_{n=0}^n a_n (\ln R)^n.$$

Temperatures predicted by this equation are within 1% of all measured calibrated temperatures. The resistances of the thermometers are measured directly by a digital multimeter. The resistance of the copper leads is negligible compared to the carbon thermometer resistance.

Thermocouples are used to measure the temperature difference between the sphere and surrounding helium. Two thermocouple junctions are soldered in the sphere with the two cold junctions in helium gas below the sphere. The tapered 2.5 cm length of the thermocouple wires is in a good contact with the sphere, which results in an estimated thermal contact error of less than 0.001  $\circ\text{C}$ . The thermocouple is Au-0.07 atomic % Fe versus chromel which is sensitive at low temperatures. A Keithly nanovoltmeter, model no. 147, is used for measuring the thermocouples output. The accuracy of the nanovoltmeter is  $\pm 2\%$  of full scale on all ranges and it can be internally calibrated. Sparks [14], in calibrating such thermocouples at the National Bureau of Standards has established stable temperature differences with drifts less than 3 mK/h and temperature accuracies of 95%. To compare with the accuracy of Sparks' calibrations, our thermocouples are calibrated against a GE thermometer by placing one junction and the germanium thermometer in a copper block and placing the other junction in a liquid helium bath. The copper block is surrounded by a heater and insulated in a nylon block. The maximum difference between our calibration and that of Sparks is 8%. Comparing the apparatus used in our calibration to that used by Sparks it is believed that the error in Sparks' calibration is less than 5%. The temperature difference is calculated using the thermocouple tables based on Sparks' calibration [14].

The power input to the sphere is found by measuring the current and the voltage. The resistance of the copper heater leads is small compared to the resistance of the heater. The vacuum is held below 0.1  $\mu\text{m}$  as monitored with an ionization gauge. It is important to maintain the helium level in the dewar above the vacuum flange in order to limit heat exchange with the pressure cylinder.

#### EXPERIMENTAL PROCEDURE

The apparatus is pre-chilled to 77 K with liquid nitrogen and then further cooled to 67 K by pumping on liquid nitrogen. After removal of liquid nitrogen the liquid helium is transferred into the outer dewar and into the pressure cylinder.

Table 1. Typical experimental results

| No. | Thermocouple          |                                       | Carbon resistance thermometer |                            | Heater power, W | Pressure, atm |
|-----|-----------------------|---------------------------------------|-------------------------------|----------------------------|-----------------|---------------|
|     | e.m.f., $\mu\text{V}$ | Temperature difference $\Delta T$ , K | Resistance $R$ , k $\Omega$   | Helium temperature $T$ , K |                 |               |
| 1   | 1.40                  | 0.096                                 | 8.61                          | 6.72                       | 0.040           | 8.0           |
| 2   | 0.85                  | 0.058                                 | 8.60                          | 6.72                       | 0.020           | 8.0           |
| 3   | 2.85                  | 0.195                                 | 8.59                          | 6.72                       | 0.098           | 8.0           |
| 4   | 4.30                  | 0.293                                 | 8.59                          | 6.72                       | 0.180           | 8.0           |
| 5   | 6.30                  | 0.428                                 | 8.58                          | 6.73                       | 0.311           | 8.0           |
| 6   | 8.30                  | 0.563                                 | 8.63                          | 6.71                       | 0.464           | 8.0           |
| 7   | 10.50                 | 0.711                                 | 8.61                          | 6.72                       | 0.636           | 8.0           |
| 8   | 13.00                 | 0.877                                 | 8.59                          | 6.72                       | 0.844           | 8.0           |
| 9   | 14.00                 | 0.943                                 | 8.57                          | 6.73                       | 0.973           | 8.0           |
| 10  | 16.50                 | 1.109                                 | 8.62                          | 6.71                       | 1.196           | 8.0           |
| 11  | 19.50                 | 1.305                                 | 8.58                          | 6.73                       | 1.477           | 8.0           |
| 12  | 23.50                 | 1.565                                 | 8.54                          | 7.74                       | 1.937           | 8.0           |
| 13  | 26.50                 | 1.759                                 | 8.50                          | 6.75                       | 2.317           | 8.0           |
| 14  | 29.50                 | 1.950                                 | 8.42                          | 6.77                       | 2.630           | 8.0           |
| 15  | 32.00                 | 2.111                                 | 8.46                          | 6.76                       | 3.010           | 8.0           |
| 16  | 35.00                 | 2.301                                 | 8.28                          | 6.79                       | 3.365           | 8.0           |

The phase space for helium in the transposed critical region is reached by initially filling the helium container with different amounts of helium. Then by supplying external heat different combinations of  $P$  and  $T$  are established. Each filling involves a particular specific volume of helium so that all measurements with that amount of helium will fall on a constant volume line, see Fig. 1. Saturated liquid helium at 4.2 K has a specific volume of  $8 \text{ cm}^3/\text{g}$ . The range of specific volumes used is  $8\text{--}18 \text{ cm}^3/\text{g}$  in order to cover the supercritical region.

The maximum pressure in the experiment is 35 atm and the maximum temperature is 25 K. At higher pressures and temperatures the effect of the critical point on heat transfer becomes negligible. The transport properties, thermal conductivity and viscosity, depend strongly on pressure at low temperature. Pressures up to 35 atm were included since no previous work has been done in the region of high pressure and low temperature.

The lowest temperature difference that could be measured is  $0.1 \pm 0.05 \text{ K}$ . At temperatures and pressures near the critical point this temperature difference is too large to achieve constant properties across a boundary layer. At higher pressures and temperatures at 0.1 K temperature difference is sufficient to achieve a constant-property experiment. The maximum temperature difference is as high as 7 K. At temperature differences higher than 7 K the heat transferred from the surface of the sphere is high and the bulk helium temperature may change appreciably during an experiment.

The quantities measured are the e.m.f. of the thermocouples, the heater power, the resistance of the carbon thermometers and the pressure. The helium inside the pressure cylinder is first heated by the heater near the bottom until the desired temperature and pressure within the supercritical region is reached, see Fig. 1. Then the heater power in the sphere is set to

achieve a given temperature difference between the sphere and helium and the heat transfer measurements are taken. A sample of these data is shown in Table 1 and all the data are tabulated in Appendix A of [13]. The thermocouple outputs are recorded using a two channel recorder, see Fig. 4. The readings of the two

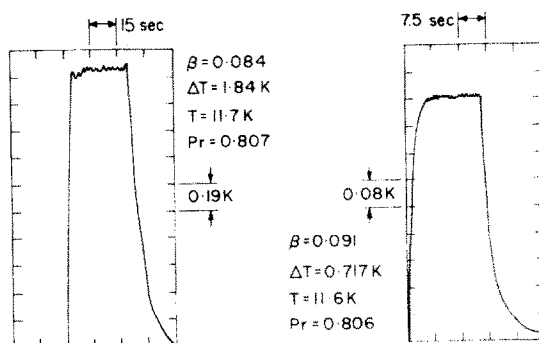


FIG. 4. Some recorded thermocouple outputs (a)  $P = 3 \text{ atm}$  and chart speed =  $3 \text{ m/h}$  (b)  $P = 27 \text{ atm}$  and chart speed =  $12 \text{ m/h}$ .

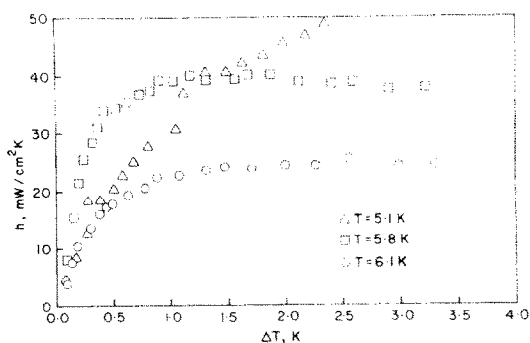


FIG. 5. Heat-transfer coefficient vs temperature difference,  $P = 3 \text{ atm}$ .

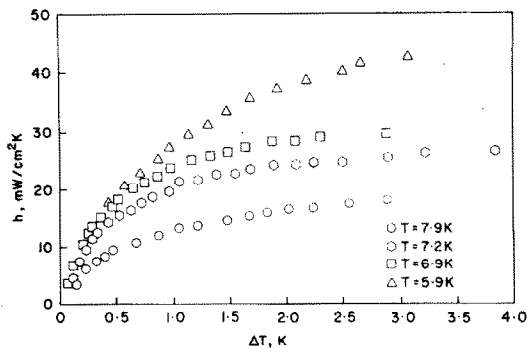


FIG. 6. Heat-transfer coefficient vs temperature difference,  $P = 5$  atm.

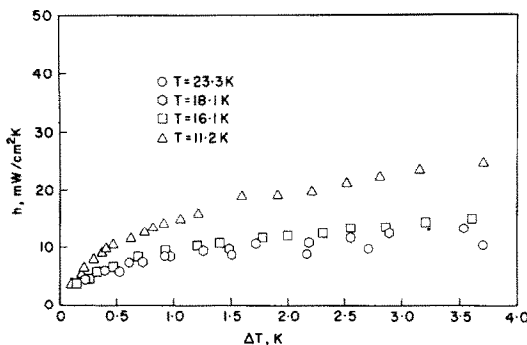


FIG. 7. Heat-transfer coefficient vs temperature difference,  $P = 25$  atm.

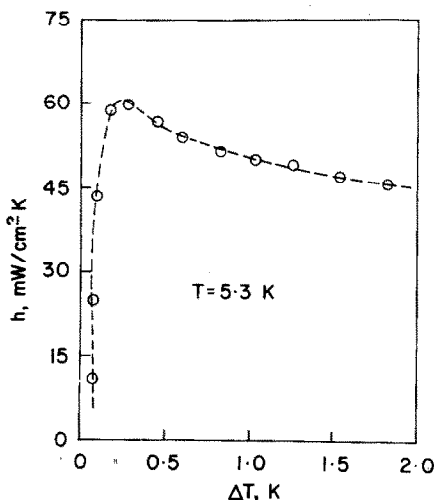


FIG. 8. Heat-transfer coefficient near the critical point to show the boiling-like phenomenon.

thermocouples are slightly different but only the output of the thermocouple junction placed in the bottom of the sphere is used in all calculations.

EXPERIMENTAL RESULTS

The heat-transfer coefficient,  $h$ , is plotted in Figs. 5–7 against  $\Delta T$  for different pressures and different temperatures. At any pressure and temperature it is seen that  $h$  increases with  $\Delta T$ . The dependence of  $h$  on  $\Delta T$  is stronger for low  $\Delta T$ . At high  $T$  and  $P$  it is found that  $h$  is lower for the same  $\Delta T$  than for low  $T$  and  $P$ , which is especially true for small  $\Delta T$ . The heat-transfer coefficient has different dependencies at temperatures and pressures very close to the critical point. Figure 8 is a plot of  $h$  against  $\Delta T$  at 2.3 atm and 5.3 K. Initially  $h$  increases with  $\Delta T$  and then decreases, which is not usual for free convection, except for work by Ito and Yamashita [15] for free convection in  $\text{CO}_2$  near the critical point.

The behavior of  $h$  near the critical point may be attributed to the occurrence of a boiling-like phenomenon associated with large changes in density. The change in density near the critical point, at  $T = 5.3$  K,  $P = 2.3$  atm and  $\Delta T = 0.1$  K, is about  $0.04 \text{ g/cm}^3$  compared to  $0.0016 \text{ g/cm}^3$  at 4 K in the liquid region at the same temperature. The large change of density in the critical region is comparable to the change in density due to a phase change, about  $0.1 \text{ g/cm}^3$  at 4.2 K. Ito and Yamashita confirmed this boiling-like phenomenon in  $\text{CO}_2$  with photographs. Irie *et al.* [10] did not report similar results since their temperature differences were relatively small. Further study of free convection heat transfer in the vicinity of the critical point is needed.

At any pressure, the specific heat, the thermal expansivity and the Prandtl number vary with tem-

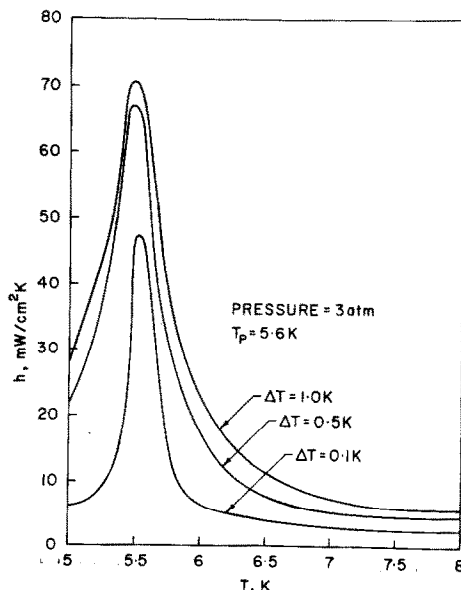


FIG. 9. Heat-transfer coefficient vs  $T$  for  $\Delta T = 0.1, 0.5$  and  $1$  K respectively.

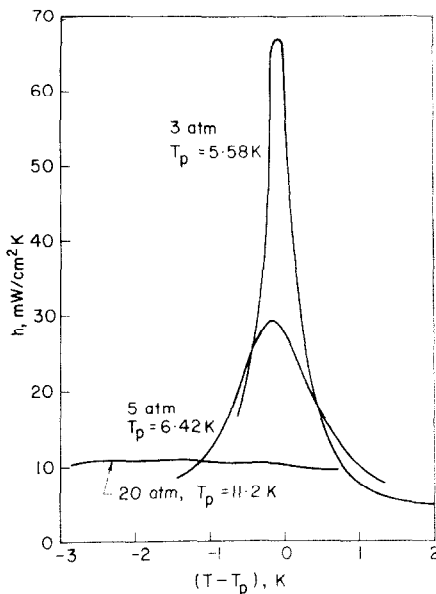


FIG. 10. Heat-transfer coefficient vs  $T - T_p$  at different pressures and for  $\Delta T = 0.5$  K.

perature and have maxima on the transposed line. The heat-transfer coefficient is expected to be a maximum on the transposed line with  $\Delta T$  held constant. Figure 9 is a plot of  $h$  for different temperatures at 3 atm in which  $h$  is found from our empirical correlations as discussed in the next section. In Fig. 10 the heat-transfer coefficient at different pressures for  $\Delta T = 0.5$  K is plotted against  $T - T_p$ , where  $T_p$  is the transposed critical temperature. Note that  $h$  is maximum at  $T = T_p$ . The maximum in  $h$  becomes smaller as the pressure is increased. For very high pressures, the maximum in  $h$  disappears.

#### EMPIRICAL CORRELATIONS

If the specific heat, viscosity, thermal conductivity and thermal expansivity of a fluid are assumed constant, then it is known that the dimensionless numbers which govern free convection are the Nusselt, Prandtl and Grashof numbers. Near the critical point other dimensionless groups should be considered since  $C_p$ ,  $\mu$ ,  $k$ , and  $\beta$  depend strongly on  $P$  and  $T$ .

For constant property fluids the relationship between the Nusselt number and the product  $GrPr$  can be expressed in exponential form as

$$Nu = C(GrPr)^a, \quad (1)$$

which is used for correlation studies of our heat-transfer measurements. The properties are first calculated at the surface temperature. A least squares method is used to find the best values of  $C$  and  $a$  and their deviations. It is found that a 100% error in evaluating  $h$  is possible using the above correlation at a temperature  $T = (T_b + T_w)/2$ .

The smallest standard deviation is obtained when the properties are calculated at the helium bulk temperature,  $T_b$ . A plot of  $\log Nu$  against  $\log(GrPr)$ , as evaluated at the bulk helium temperature, is sketched in Fig. 11. The constants  $C$  and  $a$  are found to have the values 0.0176 and 0.38, respectively. The standard deviation between the Nusselt number evaluated directly from the data and  $Nu$  calculated from the above correlation is 85. This correlation is included for comparison with the constant property case because of its simplicity.

Improvements in the correlation are achieved by including the ratio  $\Delta\rho/\rho_b$ , where  $\Delta\rho$  is the difference between  $\rho_b$  the density at the bulk temperature and  $\rho_w$  the density at the surface temperature. The need for this ratio means that the dependence of the properties on the density is important. Further improvements in the correlation are achieved by including the ratio  $T_b/\Delta T$  which is better than  $T_w/T_b$ . The ratio  $T_b/\Delta T$  was used in a heat-transfer correlation for free convection in  $CO_2$  [15]. The best correlation has the following exponential form:

$$Nu = C(T_b/\Delta T)^a(\Delta\rho/\rho_b)^b Pr^d (GrPr)^e. \quad (2)$$

The experimental data are divided into three groups according to Grashof number. The first group has a Grashof number smaller than  $2.5 \times 10^{10}$ , the second has a Grashof number larger than  $2.5 \times 10^{10}$  but smaller than  $1.25 \times 10^{11}$  and the third had a Grashof number larger than  $1.25 \times 10^{11}$ . Equation (2) is used to fit each group separately. The constants  $C$ ,  $a$ ,  $b$ ,  $d$ ,  $e$  are determined for these three groups separately using a least squares method. The values are listed in Table 2.

Figures 12–14 are plots of  $\log Nu$  against  $\log[C(T_b/\Delta T)^a(\Delta\rho/\rho_b)^b Pr^d(GrPr)^e]$  for  $Gr > 1.25 \times 10^{11}$ ,  $2.5 \times 10^{10} < Gr < 1.25 \times 10^{11}$ , and  $Gr < 2.5 \times 10^{10}$ , respectively. In these three figures correlations are represented by a straight line. In Fig. 12 for  $Gr > 1.25 \times 10^{11}$  the maximum deviation of the experimental data from correlation is  $\pm 20\%$  with the exception of four points out of a total number of 200 points. The standard deviation, for the purpose of comparison with the previous correlation is found to be 36 for this

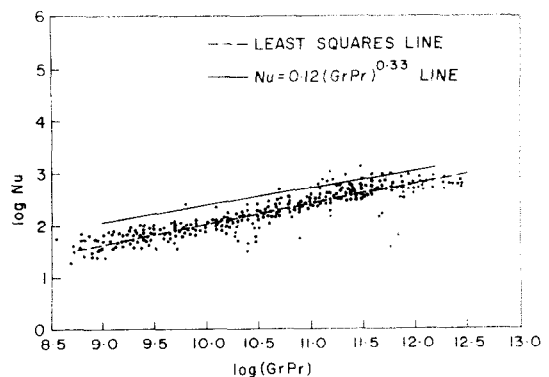


FIG. 11.  $\log(Nu)$  against  $\log(GrPr)$  for properties are evaluated at bulk temperature.

Table 2. Values of  $C$ ,  $a$ ,  $b$ ,  $d$  and  $e$  in the empirical correlation, equation (2)

| Values of $Gr$                                  | $C$   | $a$   | $b$   | $d$  | $e$  |
|---|-------|-------|-------|------|------|
| $Gr < 2.50 \times 10^{10}$                      | 2.57  | -0.55 | -0.34 | 1.07 | 0.20 |
| $2.5 \times 10^{10} < Gr < 1.25 \times 10^{11}$ | 0.154 | 0.14  | 0.25  | 0.28 | 0.30 |
| $Gr > 1.25 \times 10^{11}$                      | 0.072 | 0.32  | 0.37  | 0.16 | 0.13 |

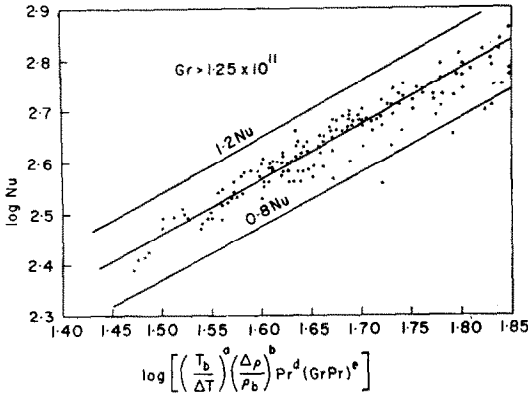


FIG. 12. Modified empirical correlation for  $Gr > 1.25 \times 10^{11}$ .

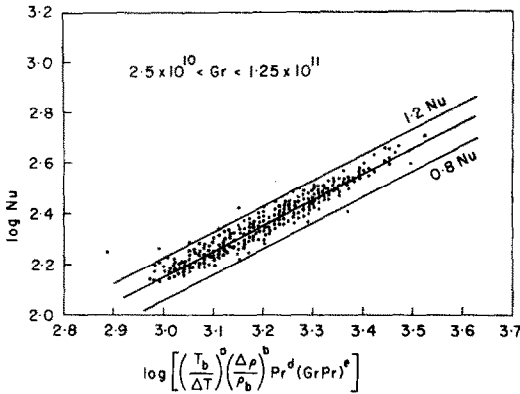


FIG. 13. Modified empirical correlation for  $2.5 \times 10^{10} < Gr < 1.25 \times 10^{11}$ .

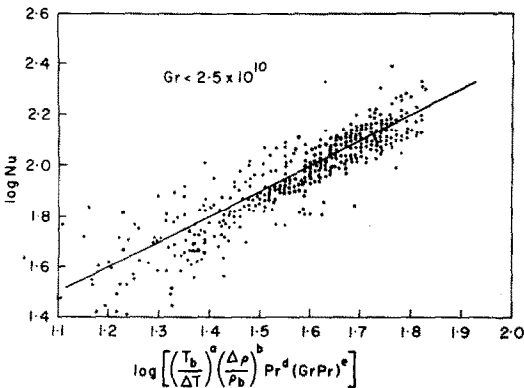


FIG. 14. Modified empirical correlation for  $Gr < 2.5 \times 10^{10}$ .

case. In Fig. 13 for  $2.5 \times 10^{10} < Gr < 1.25 \times 10^{11}$  the maximum deviation of the experimental data is  $\pm 20\%$  with the exception of four points out of 416 points at a standard deviation of 20. Nusselt numbers given by correlation can be twice the actual value for  $Gr < 2.5 \times 10^{10}$ , see Fig. 14.

COMPARISON WITH OTHER WORK

If the thermal conductivity, specific heat and thermal expansivity are considered constants then the Nusselt number will be given by equation (1), as mentioned previously. If the Grashof number is larger than  $10^8$  then the constants  $C$  and  $a$  for a sphere are 0.12 and 0.33, respectively [16]. Equation (1) is a straight line in Fig. 11, which is a plot of  $\log Nu$  against  $\log(GrPr)$  at  $T_b$ . It can be seen in Fig. 11 that the Nusselt number for most of the range is lower than the Nusselt number for the constant property case.

Figure 15 is a plot of our measurements, the previous experimental results [8-10] and the analytical Nusselt number for laminar free convection in supercritical helium [12]. The various geometries, pressures and temperatures are listed in Table 3. Since the geometries are not the same, Fig. 15 should only be used for approximate comparisons. The Nusselt and Grashof numbers in Fig. 15 are evaluated using helium bulk temperature. Our experimental studies and other previous studies show that  $h$  has a maximum on the transposed critical line which increases as the critical point is approached.

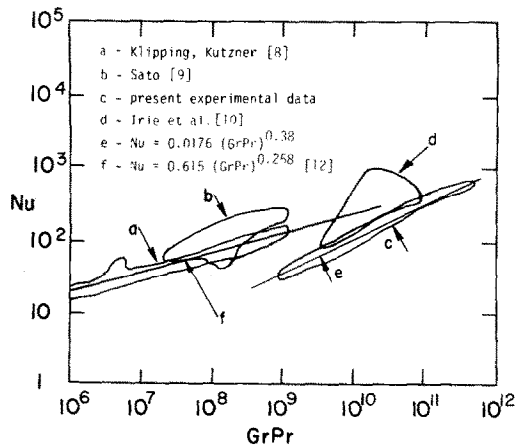


FIG. 15. Comparison of the present experimental results with previous studies.

Table 3. Different studies of free convection heat transfer to supercritical helium

| Investigator              | Geometry                | D (cm) | (Gr, Pr)                             | P (atm) | T <sub>b</sub> |
|---------------------------|-------------------------|--------|--------------------------------------|---------|----------------|
| Klippling and Kutzner [8] | Horizontal cylinder     | 0.4    | 10 <sup>5</sup> -10 <sup>9</sup>     | 1-5     | 5.4-12         |
| Sato <i>et al.</i> [9]    | Vertical cylinder       | 0.4    | 2 × 10 <sup>7</sup> -10 <sup>9</sup> | 6-16    | 4.2-7.2        |
| Irie <i>et al.</i> [10]   | Vertical cylinder       | 1.2    | ~10 <sup>10</sup>                    | 2.1-4   | 5-6            |
| Hilal [12]                | Infinite vertical plane |        | laminar                              | 3-25    | 5.6-14.3       |

## CONCLUSIONS

The heat-transfer coefficient in supercritical helium has a peak on the transposed critical lines as previously reported for other fluids [8-10]. There is very little previous work available for comparison since our measurements cover a wide range of pressures and temperatures and because other experiments did not include spherical surfaces. A correlation to our data is presented which predicts the measured heat-transfer coefficient for  $Gr > 1.25 \times 10^{11}$  and  $2.5 \times 10^{10} < Gr < 1.25 \times 10^{11}$  with 20% error.

The unpredicted feature of this experiment is a boiling-like phenomena near the critical point which has not been reported previously.

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## ETUDE EXPERIMENTALE DE LA CONVECTION THERMIQUE NATURELLE DANS L'HELIUM SUPERCRITIQUE

**Résumé** — On présente une étude expérimentale de la convection thermique naturelle autour d'une sphère de cuivre dans l'hélium supercritique. Le coefficient de convection est mesuré dans la région de la ligne critique pour des pressions entre 2,3-35 atm (0,23-3,55 MPa) et des températures entre 5,3 et 25 K. Des formules empiriques, à ± 20% sont données qui relient  $Nu$ ,  $Pr$ ,  $Gr$ ,  $\rho_b$ ,  $\Delta\rho$ ,  $T_b$ , et  $\Delta T$ . Un phénomène semblable à l'ébullition est observé près du point critique, avec croissance du coefficient de convection  $h$  en fonction de la différence de température  $\Delta T$ , jusqu'à atteindre un maximum au delà duquel  $h$  décroît pour de plus grands  $\Delta T$ .



**EINE EXPERIMENTELLE UNTERSUCHUNG DER WÄRMEÜBERTRAGUNG  
BEI FREIER KONVEKTION IN ÜBERKRITISCHEM HELIUM**

**Zusammenfassung**—Es wird über eine experimentelle Untersuchung zur Wärmeübertragung durch freie Konvektion von einer Kupferkugel an überkritisches Helium berichtet. Der Wärmeübergangskoeffizient wird im Bereich unterhalb der kritischen Linie, der Drücke von 2,3–35 atm (0,23–3,55 MPa) und Temperaturen von 5,3 bis 25 K umfaßt, gemessen. Es werden empirische Korrelationen bei einer Genauigkeit von  $\pm 20\%$  zwischen  $Nu$ ,  $Pr$ ,  $Gr$ ,  $\rho_b$ ,  $\Delta\rho$ ,  $T_b$  und  $\Delta T$  angegeben. Ein siedeähnliches Phänomen wird in der Nähe des kritischen Punkts experimentell beobachtet, wobei der Wärmeübergangskoeffizient  $h$  zunächst mit der Temperaturdifferenz  $\Delta T$  zunimmt, bis  $h$  ein Maximum erreicht und dann für größere  $\Delta T$  wieder abnimmt.

**ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ СВОБОДНОКОНВЕКТИВНОГО  
ТЕПЛООБМЕНА В СВЕРХКРИТИЧЕСКОМ ГЕЛИИ**

**Аннотация** — Проведено экспериментальное исследование свободноконвективной теплоотдачи от медного шара к сверхкритическому гелию. Коэффициент теплоотдачи измерялся в области критической линии, включающей диапазоны давлений от 2,3 до 35 атм (0,23 до 3,55 МПа) и температур от 5,3 до 25 К. С точностью до  $\pm 20\%$  получены эмпирические соотношения между  $Nu$ ,  $Pr$ ,  $Gr$ ,  $\rho_b$ ,  $\Delta\rho$ ,  $T_b$  и  $\Delta T$ . Возле критической точки наблюдалось явление типа кипения, выражающееся в том, что коэффициент теплоотдачи  $h$  увеличивается с увеличением разности температур  $\Delta T$  до тех пор, пока значение  $h$  не достигнет максимума, после чего величина  $h$  уменьшается с увеличением значения  $\Delta T$ .