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Natural convective heat transfer from a horizontal cylinder to fluid at near-critical condition

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Abstract—Experiments on natural convective heat transfer from heated horizontal cylinder to a fluid were performed for a wide range of bulk condition. At near-critical states the deviation of the dimensionless heat transfer coefficient from a Nusselt-type correlation was observed. This phenomenon may be explained by existence of three boundary layers. Copyright © 1996 Elsevier Science Ltd.

INTRODUCTION

The problem of heat transfer to fluids near their thermodynamic critical point is very difficult. The properties of a fluid have singular behavior. The classical and 'scaling' description indicates that the compressibility and the specific heat at constant pressure both become infinite at the critical point. These factors make experimentation difficult, namely, the hydrostatic pressure variations lead to significant density variation even for small changes of height and the approach to thermal equilibrium becomes slow. The coefficient of thermal expansion and the thermal conductivity strongly increase, the dynamic viscosity decreases. All these factors make it difficult to solve heat transfer problems analytically.

One of the earliest experimental investigations of natural heat transfer coefficient was performed by Schmidt *et al.* [1]. They found that heat transfer coefficient increases as the liquid approaches its critical state. The measurements were made on a closed loop. Most of the late experimental investigations of natural convection near critical point have been made using thin wires or vertical plane surfaces.

Simon and Eckert [2] experimented with a heated vertical plate. The temperature differences from a fluid to heated plate were 0.001–0.01°C and property variations were negligible. They found that heat transfer coefficient and the thermal conductivity increased with the heat flux when the fluid density was close to its critical value, but the increase in the normalized heat transfer coefficient was greater than the increase in normalized thermal conductivity. Authors suggest that the effect may be connected with the existence of clusters of molecules in the fluid at near-critical state.

Knapp and Sabersky [3] measured the heat flux from heated wire at large temperature differences. They observed a highly turbulent flow in which super-critical fluid aggregates similar to bubbles were seen to appear and disappear at the wire. There is no satisfactory explanation for this phenomenon. So, there are difficulties in describing heat transfer processes near the critical point.

One of the simplest correlations for average natural convection heat transfer coefficient is

$$Nu = f(Ra), \qquad (1)$$

where

$$Nu = \alpha d/\lambda, \quad Ra = Gr \times Pr,$$

$$Gr = g\beta\Delta T d^3/\nu^2, \quad Pr = \nu/a.$$

Neumann and Hahne [4] performed experiments of free convective heat transfer from wires to supercritical CO_2 for a wide range of bulk conditions. They found that the heat transfer coefficients can be predicted by the correlation (1). If a region of ± 2 K around the pseudocritical temperature T_{pc} (where the coefficient of thermal expansion β and specific heat capacity C_p have a sharp peaks) is spared, the properties in the Nu and Ra may be based on film temperature. Near pseudocritical state the property changes are large and heat transfer process depends upon $T_w - T_{pc}$, $T_{pc} - T_b$ and P. For each of these terms a correction function $Nu = f(Ra, f1, f2, f3)$ was determined from the experimental data. The Nu and Ra were obtained with integrated (between T_w and T_b) mean property values. All these experiments were made in laminar region ($Ra < 10^7$), but most of the free convection problems that arise in engineering are likely to give rise to turbulent regimes. In this case the dimensionless parameters governing convection are Gr, Pr, x/d, ρ/ρ_c, ν/ν_c, $C_p/(C_p)_c$, λ/λ_c [5]. Besides there is interconnection between the momentum and energy equation (temperature dependence), thus the energy

NOMENCLATURE

a	thermal diffusivity
c	specific heat
d	heater diameter
D	coefficient of diffusion
g	gravitational constant
k	compressibility
P	pressure
T	temperature
Gr	Grashof number
Nu	Nusselt number
Pr	Prandtl number
q	heat flux per unit area
Ra	Rayleigh number
x	vertical coordinate.

Greek symbols

α	heat transfer coefficient
β	coefficient of thermal expansion
λ	thermal conductivity
ν	kinematic viscosity
ρ	density.

Subscripts

b	bulk condition
c	at critical state
p	at constant pressure
pc	pseudocritical
w	heater wall.

equation remains nonlinear in temperature even if the properties are constant [5].

In this paper the experiments on natural convective heat transfer, from a 0.6 cm diameter horizontal cylinder to Freon 13 at different parameters of state, are presented.

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows the schematic sketch of the apparatus, which consists of a heater (2) mounted horizontally in a high pressure vessel (1). The vessel has an inner cross section of 10 × 10 cm and 20 cm inner height. Glass windows (4) and (5) allow for Schlieren projections (13–17). Temperature of a tank (6) was measured by platinum thermoresistor (7). The water was pumped from the thermostat (8). The temperature of the balk fluid was measured by ten thermoresistors (3) located at various levels.

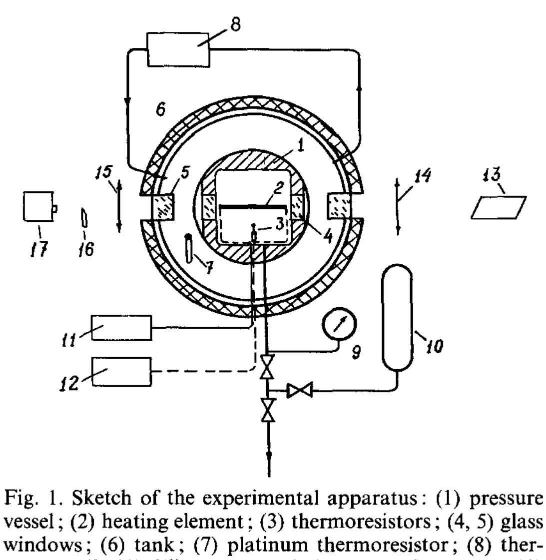

Fig. 1. Sketch of the experimental apparatus: (1) pressure vessel; (2) heating element; (3) thermoresistors; (4, 5) glass windows; (6) tank; (7) platinum thermoresistor; (8) thermostat; (9, 10) filling system; (11) source of current; (12) voltmeter; (13) He–Ne laser; (14, 15) lenses; (16) knife; (17) camera.

The heater and its place in test section are presented in Fig. 2. The heater consists of an electrically heated nichrome wire. It is surrounded by cylindrical ceramic and copper pipes to form a concentrical annulus. The temperature drop δT between the thermoresistor location and the heater surface is a function of the heat flux and the ratio between the distance of thermoresistor from the surface s and the thermal conductivity of the copper λ_l. It can be estimated as $\delta T \sim qs/\lambda_l$. These variances in our experiments were about 0.5% and were neglected in calculations. The heat transfer coefficient is defined as

$$\alpha = q/(T_w - T_b).$$

The filling system (9–10) serves to fill the test section by R-13 ($CClF_3$) which has the critical parameters $P_c = 3.96$ MPa, $T_c = 302.02$K, $\rho_c = 0.58$ g cm^{-3}.

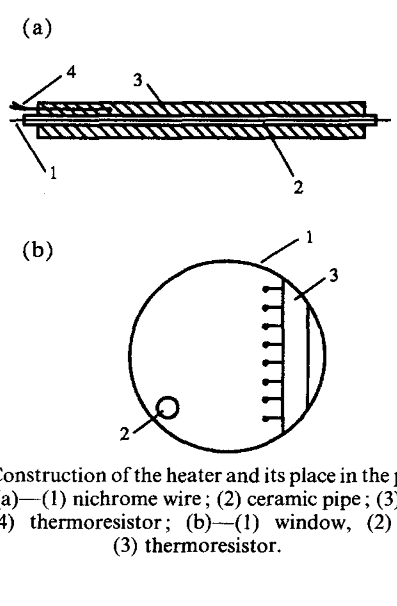

Fig. 2. Construction of the heater and its place in the pressure vessel: (a)—(1) nichrome wire; (2) ceramic pipe; (3) copper pipe; (4) thermoresistor; (b)—(1) window, (2) heater, (3) thermoresistor.

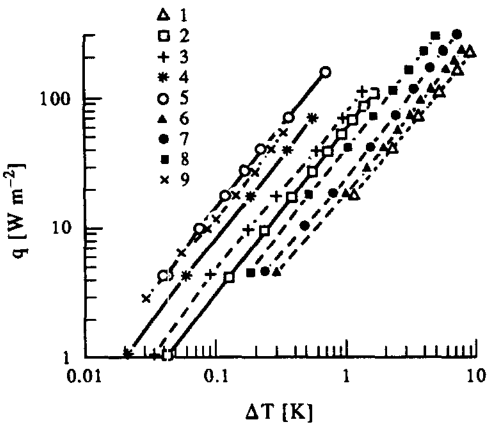

Fig. 3. Heat flux vs temperature difference: (1) $\rho_b = 0.029$ g cm^{-3}, $T_b = 12°C$; (2) $\rho_b = 0.215$ g cm^{-3}, $T_b = 29°C$; (3) $\rho_b = 0.235$ g cm^{-3}, $T_b = 29°C$; (4) $\rho_b = 0.33$ g cm^{-3}, $T_b = 29°C$; (5) $\rho_b = 0.41$ g cm^{-3}, $T_b = 29°C$; (6) $\rho_b = 0.043$ g cm^{-3}, $T_b = 40°C$; (7) $\rho_b = 0.083$ g cm^{-3}, $T_b = 40°C$; (8) $\rho_b = 0.15$ g cm^{-3}, $T_b = 40°C$; (9) $\rho_b = 0.49$ g cm^{-3}, $T_b = 40°C$.

All the temperature and pressure data were recorded into the IBM PC.

EXPERIMENTAL RESULTS

Experimental data for heat flux as a function of temperature difference $\Delta T = T_w - T_b$ are presented in Fig. 3. As the critical state is approached the smaller temperature differences are necessary to transfer the same flux from the heater to the fluid. Typical results for heat transfer coefficients as a function of wall temperatures are presented in Fig. 4.

When T_b and ρ_b are 'far' from critical values ($\rho_b = 0.029$, $T_b = 12$; $\rho_b = 0.043$, $T_b = 40$; $\rho_b = 0.083$, $T_b = 40$) the heat transfer coefficient increases to a nearly constant value with the increase of T_w (ρ_b are presented in g cm^{-3} and T_b in °C). With the increase of the bulk density, the coefficient

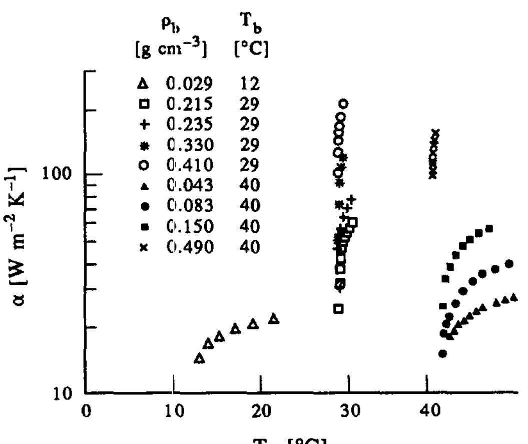

Fig. 4. Heat transfer coefficient depending on wall temperature.

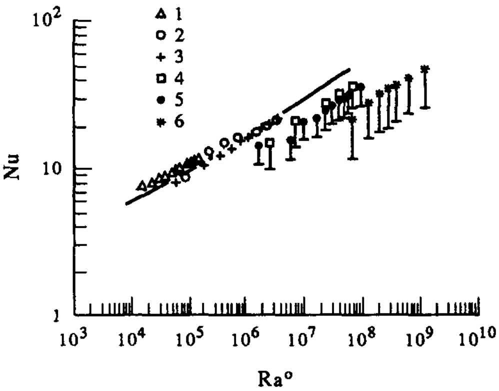

Fig. 5. Correlation of measured data according to equation (2): (1) $\rho_b = 0.043$ g cm^{-3}, $T_b = 40°C$; (2) $\rho_b = 0.235$ g cm^{-3}, $T_b = 29°C$; (3) $\rho = 0.215$ g cm^{-3}, $T_b = 29°C$; (4) $\rho_b = 0.49$ g cm^{-3}, $T_b = 40°C$; (5) $\rho_b = 0.33$ g cm^{-3}, $T_b = 29°C$; (6) $\rho_b = 0.41$ g cm^{-3}, $T_b = 29°C$.

increases too, but it remains at comparatively small values ($\rho_b = 0.15$, $T_b = 40$).

With a further increase of ρ_b the heat transfer coefficient and its rate of change becomes more significant ($\rho_b = 0.49$, $T_b = 40$). The same picture is observed with $T_b \sim T_c$.

Although the properties near critical state are anomaly dependent on temperature and the processes are not physically similar, it is commonly accepted to use equation (1) for the correlation of experimental data.

Figure 5 shows the experimental data in terms of Nu and Ra°

$$Nu = 0.518(Ra^\circ)^{0.25},$$

$$Ra^\circ = Ra/[1+(0.559/Pr)^{9/16}]^{16/9}. \quad (2)$$

Churchill and Chu [6] have suggested this semi-empirical correlation for heat transfer by natural convection from horizontal cylinders for all Pr and for $10^{-6} < Ra < 10^9$. Here, this correlation is corrected by term $\delta Nu = 2 \ln(1+2/Nu)$ suggested by Langmuir [7] for cylinders.

The thermal properties were taken at film temperature $(T_w - T_b)/2$ from the papers [8, 9]. One can see that there are two cases of heat transfer. When the properties do not have anomalies (1)–(3) the heat transfer coefficient can be predicted by the correlation (2). When the properties have anomalies we observed the deviation of data from the correlation. The calculations Nu as a function of Ra (4)–(7) were made without considering the anomaly term $\Delta\lambda$. The overall uncertainties conclude the anomaly parts in λ.

DISCUSSION AND CONCLUSION

We suggest that the deviation may be connected with the existence of double diffusion in the fluid at near-critical conditions. From our point of view there are three boundary layers near the heated surface. Besides dynamic (δ_D) and thermal (δ_T) a 'diffusive' boundary layer (δ_*) appears at near-critical state (when $D < a$).

$$\delta_D^2/\nu \sim \delta_T^2/a \sim \delta_*^2/D.$$

One of the dimensionless parameters governing free convection is the Grashof Number $Gr = gd^3\Delta\rho/\rho\nu^2$ where $\Delta\rho$ is a characteristic density difference, usually that between the fluid at the heated surface and that outside the thermal layer.

In our case a density difference appears only in layer with thickness δ_*. It leads to correction of equation (1)

$$Nu = f(Gr, Pr, D/a).$$

In laminar region the correlation (2) arises in the form

$$Nu = 0.518(Ra^\circ)^{0.25} f(D/a), \quad \text{where } f(D/a) < 1.$$

D is coefficient of diffusion at isothermal conditions. Skripov [10] has obtained the expression for mass flux j in a slightly unequilibrium on density fluid in the vicinity of the critical state at constant temperature.

$$j = -D\cdot\nabla\rho, \quad \text{where } D = (L/\rho^2)\cdot k_T^{-1}.$$

k_T is the coefficient of the isothermal compressibility, L is the kinetic coefficient. Because at $\rho = \rho_c$ $k_T \sim (T-T_c)^{-1.2}$, the coefficient D strongly decreases near the critical point. The situation when $D < a$ may appear. Substitution of $\Delta\rho$ on $\beta\Delta T$ becomes wrong and Grashof number decreases. So the deviation of experimental data from the correlation (2) may be explained by suggested model.

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