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A method for researching natural convection heat transfer from a non-isothermal vertical plate by infra-red thermovision

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Abstract—The modern infra-red thermovision technique is introduced to measure the surface temperature distribution on a vertical plate. The temperature distributions of air in natural convection and hence the local Nusselt number are calculated numerically. Natural convection heat transfer for a vertical plate with a horizontal discrete heating surface is studied as a working example, and typical results are reported and discussed. It is clear that, such a method not only benefits the research on natural convection heat transfer but also extends the field of application for infra-red thermovision.

1. INTRODUCTION

RESEARCH on the natural convection heat transfer from a vertical plate surface to the surrounding fluid has been going on for more than 100 years, and scientists have carried out both theoretically and experimental works [1–3]. Studies have been carried out for an isothermal plate [2–4], for a constant heat flux at the plate surface [5], or for the surface temperature distribution in either power-law variation or exponential variation [3, 6]. However, for the natural convection heat transfer from discrete heaters on a vertical plate, usually encountered in the cooling of electronic equipment or devices, the boundary conditions are much more complicated. Zimin and Lyakhov [7] studied first in 1970 the flow due to a single line thermal source on a vertical plate experimentally and analytically. Jaluria and Gebhart [8] analysed the problem of boundary layer flow arising from a line thermal source on a vertical plate by the similarity method, and Jaluria [9] investigated the flow due to a finite height source on a vertical plate by the finite difference method. Jaluria [10], and Sparrow and Faghri [11] studied the interaction of the flows due to multiple sources on a vertical plate with finite difference methods also. They all assumed that the unheated surfaces were adiabatic, i.e. no heat was conducted from the heated to the unheated section and no heat was conducted to the surrounding fluid. Recently, Kishinami and Saito [12] considered the effect of heat conduction in a vertical plate on natural convection flow and presented the numerical solution for the natural convection heat transfer from a vertical plate with discontinuous surface temperature, assuming an isothermal heated surface. Zinnes [13] also considered the effect of heat conduction in the plate on the temperture field generated by finite heating elements and presented the corresponding numerical solution which has a more cumbersome procedure.

In this paper, we will report a method by taking advantage of the modern infra-red thermovision to measure the actual arbitrary temperature distribution on the surface of a vertical plate, then the fluid temperature field and hence the local Nusselt number for natural convection arising from the discrete thermal sources on a vertical plate will be calculated numerically.

2. BASIC IDEA

For a Newtonian fluid and with the Boussinesq assumption, the governing equations for the natural convection heat transfer from a vertical plate, with a one-dimensional surface temperature distribution, $T_w(x)$, to the surroundings as shown in Fig. 1, will be

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=g\beta(T-T_\infty)+v\frac{\partial^2 u}{\partial x^2} \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=a\frac{\partial^2 T}{\partial y^2}. \tag{3}$$

The corresponding boundary conditions are

$$\left.\begin{array}{l} y=0,\quad u=0,\quad v=0,\quad \text{and}\quad T=T_w(x)\\ y\to\infty,\quad u=0,\quad \text{and}\quad T=T_\infty\\ x=-b,\quad \text{i.e. at the bottom of vertical plate,}\\ \qquad u=0,\quad \text{and}\quad T=T_\infty. \end{array}\right\} \tag{4}$$

Here, T is the fluid temperature, u and v the fluid velocity components in the x- and y-directions, respectively, a and v the thermal diffusivity and kinematic viscosity of fluid, and β the coefficient of the thermal expansion of fluid.

Introducing the following dimensionless variables:

$$X=x/h,\quad Y=y/h,\quad U=uh/v,\quad V=vh/v,$$

NOMENCLATURE

a	thermal diffusivity [$\mathrm{m^2\,s^{-1}}$]
g	gravitational acceleration [$\mathrm{m\,s^{-2}}$]
Gr	Grashof number
h	height of the vertical plate [m]
Nu	Nusselt number
Pr	Prandtl number
T	temperature [°C]
u, v	velocity components in the x- and y-directions, respectively [$\mathrm{m\,s^{-1}}$]
w	width of the plate [m]
x, y	coordinates [m].

Greek symbols

β	coefficient of thermal expansion of fluid [$\mathrm{K^{-1}}$]
θ	normalized temperature, $(T-T_\infty)/(T_w-T_\infty)$
ν	kinematic viscosity of fluid [$\mathrm{m^2\,s^{-1}}$].

Subscripts

w	at the wall surface
∞	surrounding fluid.

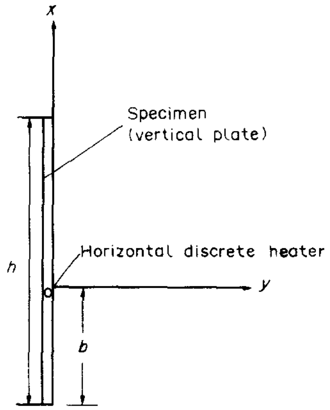

FIG. 1. Coordinate system.

$$Pr = a/\nu, \quad Gr = g\beta(T_w - T_\infty)h^3/\nu^2$$

and the dimensionless normalized temperature $\theta = (T-T_\infty)/(T_w-T_\infty)$, then, governing equations (1)–(3) could be transformed into dimensionless form as

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{5}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = Gr\,\theta + \frac{\partial^2 U}{\partial Y^2} \tag{6}$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{Pr}\frac{\partial^2 \theta}{\partial Y^2}. \tag{7}$$

The corresponding dimensionless boundary conditions can be taken from equation (4) as

$$\left.\begin{array}{llll} Y = 0, & U = 0, & V = 0, & \theta = 1 \\ Y \to \infty, & U = 0 & \text{and} & \theta = 0 \\ X = -b/h, & U = 0 & \text{and} & \theta = 0. \end{array}\right\} \tag{8}$$

It is clear that, the temperature field of fluid in natural convection could be determined analytically from the governing equations and corresponding boundary conditions knowing T_∞ and $T_w(X)$. The ambient temperature, T_∞, is usually kept constant, and so, can be measured easily. The surface temperature distribution, $T_w(x)$, may be measured with thermocouples, but the temperature field thus found will be discontinuous and disturbed by the embedded thermocouples. The infra-red thermovision scanning technique is introduced to measure the actual surface temperature distribution of a vertical plate. In this way, not only to avoid any physical contact with the surface, it would be possible to measure the actual arbitrary surface temperature distribution with high precision.

3. NATURAL CONVECTION HEAT TRANSFER FROM HORIZONTAL DISCRETE HEATERS ON A VERTICAL PLATE

As an actual working example, we have studied the natural convection heat transfer from a vertical plate, made of epoxy glass, to surrounding air. The vertical plate was 150 × 150 mm ($h \times w$) and 2 mm thick. A discrete thermal source, consisting of a resistance heater of 0.1 mm nickel–chrome shim stock, 2 × 150 mm ($h \times w$), was mounted horizontally at the location shown in Fig. 2.

In order to determine the space location of the thermogram, we embedded two thermocouples and two metallic short strips. The temperature measured by the thermocouple was also used to calculate the surface emissivity of the vertical plate combined with the temperature of the corresponding location measured by thermovision. The surface of the nickel-chrome shim stock was painted black with carbon-ink to enhance its emissivity and thus improve the surface-temperature measuring accuracy of thermovision [14]. The experiments were carried out with ambient air temperature being kept steady and constant.

Figure 3 shows a typical thermogram of the surface temperature distribution measured with thermovision AGA 780. The 'low temperature zone' shows the location of the metallic short strip, the emissivity of which is much lower than that of the plate. Shifting the scanning line along the x-direction, we have the surface temperature distribution $T_w(x)$, like that plot-

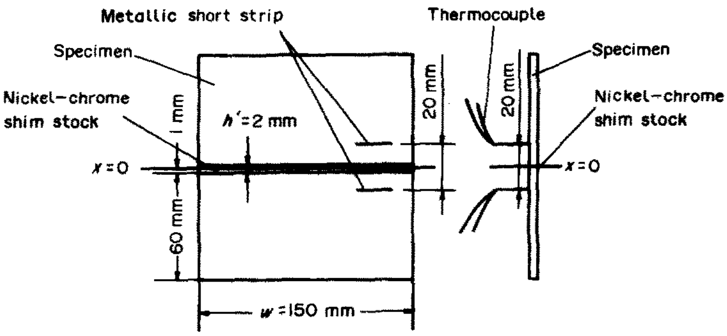

FIG. 2. Heater and space location.

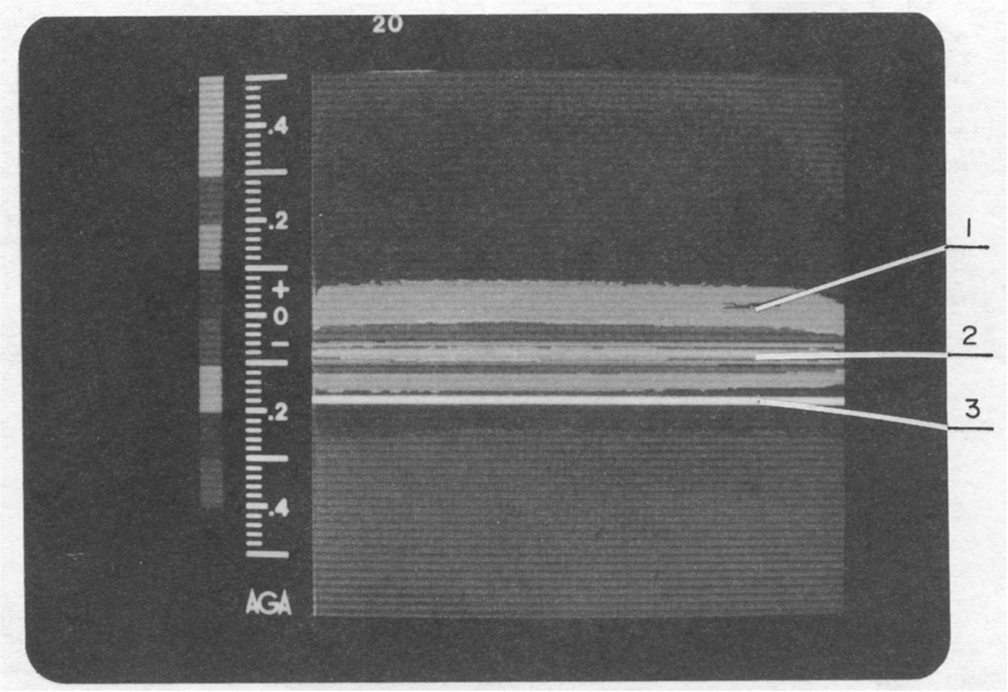

FIG. 3. Typical thermogram: 1, 'low temperature zone'; 2, heater zone; 3, profile scanning line.

ted in Fig. 4. The discrete surface temperature taken from the thermogram and the measured surrounding air temperature were used to calculate the temperature field of air as natural convection. The finite difference method (FDM) was adopted [15], and the corresponding result for the air temperature field obtained numerically is shown in Fig. 5.

We can therefore calculate the local Nusselt number from the known temperature field of air as

$$Nu_x = \left(\frac{\partial \theta}{\partial Y}\right)_{Y=0}. \qquad (9)$$

Figure 6 shows the typical numerical result for the local Nusselt number distribution.

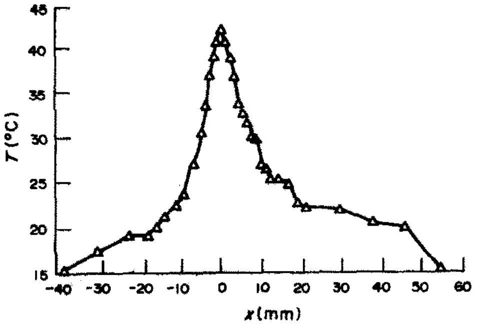

FIG. 4. The surface temperature distribution measured by thermovision.

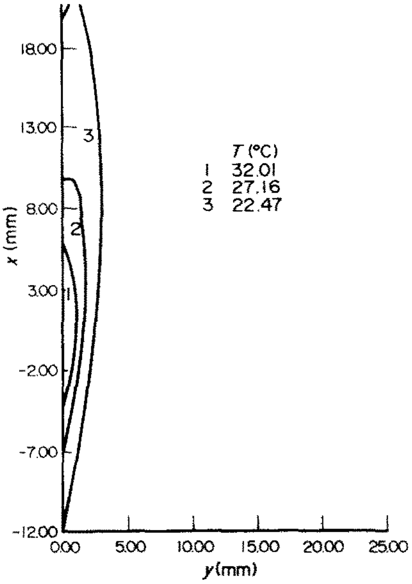

FIG. 5. The temperature field of air obtained by numerical calculation.

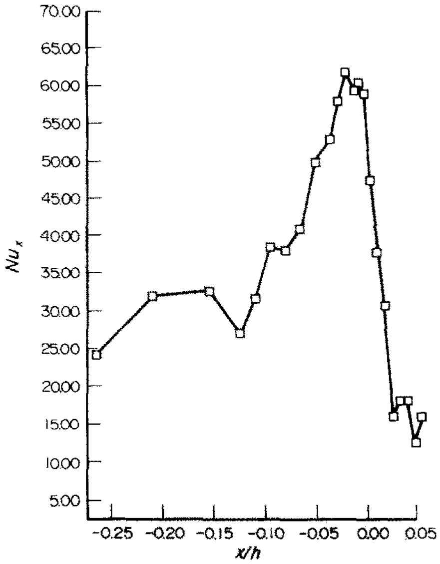

FIG. 6. Local Nusselt number vs x/h.

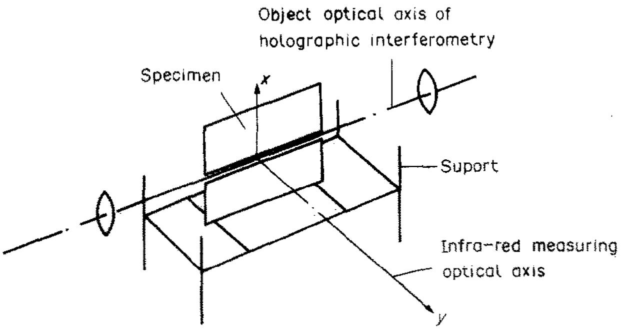

FIG. 7. Measuring system.

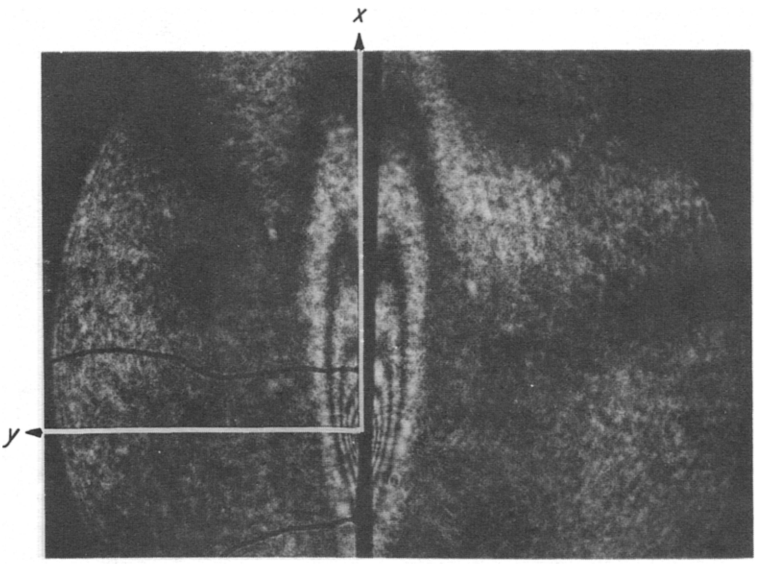

FIG. 8. An infinite-fringe hologram of the thermal field of air.

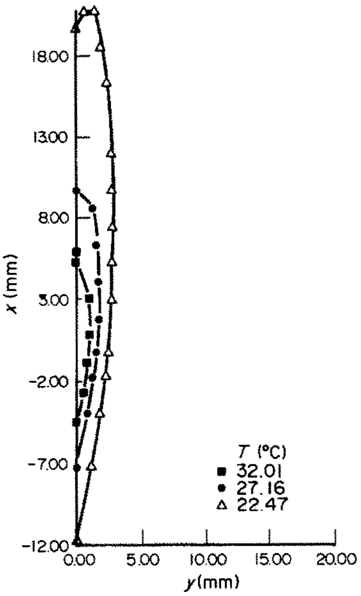

FIG. 9. The temperature field of air measured by holographic interferometry.

4. EXPERIMENTAL CHECK WITH LASER HOLOGRAPHY FOR PREDICTED AIR TEMPERATURE FIELD

To examine the reliability of the method mentioned above, we measured the temperature field of the surrounding air in natural convection by laser holographic interferometer type HIF-12 made in Germany. The schematic diagram of the measuring system is shown in Fig. 7. Figure 8 shows a typical hologram, from which we obtained the corresponding air temperature field as shown in Fig. 9.

We found that the predicted air temperature fields deviate from actual measured ones by less than 4% [16].

5. CONCLUSION

One can conclude that the method proposed here will be reliable and attractive for researching natural convection heat transfer from an arbitrary non-isothermal plate surface or from a plate with any uneven distributed surface heat flux. Infra-red thermovision could serve as an effective tool for studying natural convection heat transfer, and so, our work will extend the field of application for infra-red thermovision.

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UNE METHODE D'ETUDE PAR THERMOVISION INFRAROUGE DU TRANSFERT THERMIQUE DE CONVECTION NATURELLE

Résumé—La technique moderne de thermovision infrarouge est introduite pour mesurer la distribution de température de la surface d'une plaque verticale. Les distributions de température de l'air en convection naturelle et par suite le nombre de Nusselt local sont calculées numériquement. Le transfert thermique par convection naturelle sur une plaque verticale avec une surface de chauffage horizontale discrète est étudié comme exemple et les résultats typiques sont reportés et discutés. Il est clair qu'une telle méthode n'est pas seulement utile pour la convection naturelle mais aussi elle étend le champ d'application de la thermovision infrarouge.

UNTERSUCHUNG DES WÄRMEÜBERGANGS BEI NATÜRLICHER KONVEKTION AN EINER NICHT-ISOTHERMEN SENKRECHTEN PLATTE MITTELS INFRAROTTHERMOGRAPHIE

Zusammenfassung—Mit Hilfe der Infrarotthermographie wird die Oberflächentemperatur einer senkrechten Platte gemessen. Außerdem wird die Temperaturverteilung bei natürlicher Konvektion in Luft und daraus die Verteilung der örtlichen Nusselt-Zahl numerisch berechnet. Als Beispiel wird die natürliche Konvektion an einer senkrechten Platte mit einer waagerecht angebrachten Heizzone untersucht. Typische Ergebnisse werden dargestellt und diskutiert. Es liegt auf der Hand, daß ein derartiges Verfahren nicht nur Vorteile bietet für die Untersuchungen des Wärmeübergangs bei natürlicher Konvektion, sondern auch das Feld der Anwendungen der Infrarotthermographie erweitert.

МЕТОД ИССЛЕДОВАНИЯ ТЕПЛОПЕРЕНОСА ПРИ ЕСТЕСТВЕННОЙ КОНВЕКЦИИ НА НЕИЗОТЕРМИЧЕСКОЙ ВЕРТИКАЛЬНОЙ ПЛАСТИНЕ С ИСПОЛЬЗОВАНИЕМ ИНФРАКРАСНОГО ТЕПЛОВИДЕНИЯ

Аннотация—Современная технология инфракрасного тепловидения используется для измерения распределения температур по поверхности вертикальной пластины. Численно определяется распределение температур воздуха при естественной конвекции, а из него—локальное число Нуссельта. В качестве примера исследуется теплоперенос при естественной конвекции у вертикальной пластины с горизонтальной дискретной поверхностью нагрева, обсуждаются полученные результаты. Очевидно, что применение указанного метода не только является успешным при исследовании теплопереноса при естественной конвекции, но также расширяет область применения инфракрасного тепловидения.