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# AN EXPERIMENTAL ANALYSIS OF THE PERFORMANCE OF A SHORT BAR IN FREE CONVECTION HEAT TRANSFER

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## ABSTRACT

In this work, we present the experimental evaluation of an apparatus that is meant to assess the heat transfer in natural convection conditions for short bars, using water as cooling down fluid. The probe was fabricated in copper, with 150 mm length and 25.4 mm internal diameter. The prototype was completely instrumented to obtain the convective coefficient and the values of the involved physical variables were registered using the Labview software. Heat was supplied with a 500 W electrical resistance regulated by an electronic rheostat. Temperature in different zones was registered using 50 K type thermocouples. The maximum temperature value was registered at the initial extreme of the bar which was 48.3 °C; at a radial distance of 0.003 m it was 43.1 °C and at 0.05 m, 35.2°C. Near the final extreme of the bar, the measured values were 36.6, 35.0, and 31.4 °C respectively. The initial temperature of the fluid and the environment were constant at 20 °C. A simulation of the experiment was performed using the Comsol Multiphysics software, obtaining an acceptable similitude.

## INTRODUCTION

Natural convection in opened-ended horizontal short bars is a very important subject in both academic studies and industrial research, including drying processes, solar receiver systems, fire safety research and the deposition process in semiconductor manufacturing. The location of the heated surface installed on one side of horizontal short bar will cause the natural convection phenomenon to be affected. The installation of the heated surface on the bottom of the bar promotes an unsteadily ascending flow. In this process, the density of the fluid decreases gradually as the fluid passes over the heat surface. The velocity of the fluid is then steadily accelerated by the variable buoyancy force. As a result, there is a possibility to change the flow field from steady to unsteady in the duration of the heating process. That is rather different from the flow field occurring in the forced convection in which an invariable velocity of fluid is assigned by the given condition in advance. Therefore, when this subject is investigated using a numerical study, two thorny problems are observed. One is the treatment of boundary conditions at both opened-ended apertures; the other is the development of a proper and efficient computation method for resolving the variations of the flow and thermal fields from a steady to an unsteady situation during the heating process.

## NOMENCLATURE

| | | |
|---|---|---|
| $Q_e$ | [W] | *Entrance heat* |
| $Q_{cond}$ | [W] | Conduction heat |
| $Q_{conv}$ | [W] | Convective heat |
| $h$ | [W/m$^3$] | Convection coefficient |
| $k$ | [W/m$^2$K] | Thermal conductivity |
| $R$ | [m$^2$K/W] | Interfacial thermal resistance |
| $T$ | [K] | Temperature |
| $T_w$ | [K] | Wall temperature |
| $T_\infty$ | [K] | Environment temperature |
| $u$ | [m/s] | x-velocity |
| $v$ | [m/s] | y-velocity |
| $x$ | [m] | Cartesian axis direction |
| $p$ | [Pa] | Pressure |
| $g$ | [m/s$^2$] | Gravity |

Special characters

| | | |
|---|---|---|
| $\rho$ | [kg/m$^3$] | Density |
| $\mu$ | [N s/m$^2$] | Viscosity |
| $\alpha$ | [m$^2$/s] | thermal diffusivity |
| $\beta$ | [1/Km] | coefficient of volume expansion of the fluid |

In order to facilitate the theoretical analyses of the subject mentioned above, various authors [1–3] adopted the Boussinesq assumption which is available for the temperature differences of natural convection to investigate the phenomena of natural convection. The Boussinesq assumption implies that the density of the fluid is regarded as a constant except in the term of the buoyancy force, which is a driving force of natural convection, is an invariable parameter. The indication of flow field varying from a steady to an unsteady situation caused by the gradual acceleration of flow field in the duration of the heating process mentioned above is difficult to be explained.

The goal of this work was to present the experimental evaluation of an apparatus that is meant to assess the heat transfer in natural convection conditions for short bars, using water as cooling down fluid. The prototype was completely instrumented to obtain the values of the involved physical variables; they were registered using the Labview software. A simulation of the experiment was performed using the COMSOL Multiphysics software, obtaining an acceptable similitude.

## EXPERIMENTAL APPARATUS

The probe was fabricated in copper, with 150 mm length and 25.4 mm internal diameter. The deposit which contains the cooling fluid has a transversal section of 200 mm and 250 mm length. The probe was placed horizontally in the central position. Heat was supplied with a 500 W electrical resistance regulated by an electronic rheostat. This resistance surrounded one of the ends of the probe and was covered with an insulating material; to avoid energy loses towards the environment. The used apparatus is presented in figure 1.

Ten uniformly distributed thermocouples were used to measure the temperature on the surface of the probe. The thermocouples were J type. The cooling down fluid in all tests was water initially at 20 °C. To measure the temperature in the fluid two crossed meshes, with 5 vertical and 5 horizontal measurement points, symmetrically arranged were adapted. These meshes were perpendicularly locates in the same place as the thermocouples. Temperatures were registered every minute using the Labview software. Once the experiment was over, it was repeated for a different set of locations (thermocouples and meshes) in order to complete the register of the temperature distribution in the probe and the surrounding water.

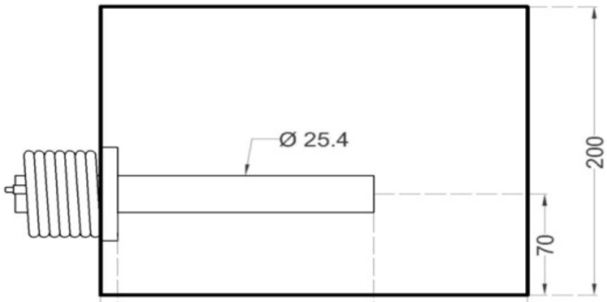

Figure 1. Experimental apparatus.

## EXPERIMENTAL PROCEDURE

The probe was set within the recipient with its ten thermocouples. The two meshes adapted with 20 thermocouples were located exactly over the probe thermocouples. All the thermocouples were connected via ADAM modules to the computer. A known volume of water was poured into the recipient. The test started when the temperature in all thermocouples was the same, approximately 20 °C and the water was static. A 500 W power was supplied to the resistance. The software was programmed to register the data every minute during half an hour. This procedure was repeated twice, using different locations until the complete picture was obtained.

The energy conservation equation states that all the heat supplied to the electrical resistance should pass to the bar via conduction and afterward be distributed in the surrounding fluid by convection, that is

$$Q_e = Q_{cond} = Q_{conv} \tag{1}$$

And the heat is equal to,

$$Q_{conv} = hA(T_w - T_\infty) \tag{2}$$

In which $h$ is the convection coefficient, $A$ is the cross-section of the bar, $T_w$ is the temperature at the wall and $T_\infty$ is the temperature of the fluid.

## MATHEMATICAL FORMULATION

The study of natural convection of a Newtonian fluid from a vertical plate with both constant surface temperature and constant wall heat flux is given by Burmeister [4]. Schlichting and Gersten [5] have presented a similarity solution for natural convection of a Newtonian fluid past a horizontal plate, which they referred to as ‘‘indirect natural convection’’ for the reasons explained in the second paragraph. According to them, the first similarity solution for isothermal, semi-infinite, horizontal plate was given by Stewartson [6] who studied the case of a fluid with Pr = 0.7. Rotem and Claassen [7] studied the problem of free convection over a semi-infinite horizontal plate for power-law variation in plate temperature and constant wall heat flux, and through experiments showed how the boundary layer breaks down into large-eddy instability some distance from the leading edge. Recently, a similarity solution for natural convection of a Newtonian fluid for complex boundary conditions has been given by Samanta and Guha [8], a boundary layer analysis is performed for the steady laminar natural convection of an electrically conducting viscous incompressible fluid above a horizontal plate in the presence of a transverse magnetic field, they used water in their analysis.

The x-axis is aligned along the short bar from the leading edge while the y-axis is directed normal to the bar against the direction of gravity. The quiescent ambient fluid is maintained at a uniform temperature $T_\infty$ and pressure $p_\infty$. The boundary layer equations for a horizontal plate invoking the Boussinesq approximation are:

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3}$$

x-momentum equation:

$$u\frac{\partial u}{\partial x}+\ v\frac{\partial u}{\partial y}=-\ \frac{1}{\rho}\ \frac{\partial p}{\partial x}+\frac{1}{\rho}\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) \qquad (4)$$

y-momentum equation:

$$0\ =\ \frac{1}{\rho}\ \frac{\partial p}{\partial y}+g\beta(T-T_\infty) \qquad (5)$$

Energy equation:

$$u\frac{\partial T}{\partial x}+\ v\frac{\partial T}{\partial y}=\ \alpha\ \frac{\partial^2 T}{\partial y^2} \qquad (6)$$

The boundary conditions are:

$$\text{at } y=0, u=0, v=0, T=\ T_w \qquad (7)$$

$$\text{as } y\to\infty, u\to 0, T\to T_\infty, p\to p_\infty \qquad (8)$$

Here, $u$ and $v$ are the components of velocity along the $x$ and $y$ axes respectively, $T$ is the local temperature of the fluid, $\mu$ is the base viscosity of the fluid, $g$ is the magnitude of the acceleration due to gravity, $\beta$ is the coefficient of volume expansion of the fluid, $\alpha$ is the thermal diffusivity, $\rho$ is the density of the fluid, $C_p$ is the specific heat capacity of the fluid.
It is a reasonable approximation in interiors, if one only considers regions whose height is much smaller than the local density and temperature scale heights. The idea behind that restriction is that if the background state does not very much, then even if a large scale flow moves a fluid element from the bottom to the top of the domain (and vice versa), the difference between temperature and density in the element and in the ambient fluid will never be very large, Kundu and Cohen [9].

To solve the conservation equations the COMSOL multiphysics software was used with the imposed boundary conditions.

## RESULTS AND DISCUSSION

At the beginning of the experimental test the temperature of the fluid was 20 °C, similar to the environment temperature. This value was constant through the whole test.

After 30 minutes, the base of the probe was at 48.3 °C, and it gradually decreased down to the final edge to 36.6 °C. At a vertical distance of 0.003 m over the probe, the registered temperature was 43.1 °C at the initial extreme of the probe 33.0 °C at the final edge. The distribution of the registered temperature is presented in a figure 2. The temperature in the free surface of the fluid at the initial extreme of the probe was 35.0 °C and 31.4 °C at the final extreme. The variation of the temperatures between the surface of the probe and those registered at a distance of 0.003 m was almost constant along the probe, with an average value of 4 °C, The convection coefficient, h, could be obtained with these values and using equation (2).

The distribution of temperatures and velocities obtained with the COMSOL software is shown in figures 3 and 4 respectively. The isotherms are presented in figure 3, where it can be noticed that at the initial extreme of the bar the temperature is 60 °C, at the center it is 47 °C and in the final extreme it is 44 °C. These temperatures are 20 % higher than the experimental ones, for the same bar lengths. The temperature of the fluid at 0.003 m from the bar, were 42 °C, 39 °C and 38 °C, respectively. Comparing them with the experimental temperatures, the difference in average is less than 5%. At the free surface of the fluid at the beginning of the bar it was 38 °C, and 35°C at the final extreme, these temperatures are almost 5% higher than those obtained in the experiment. The graph of these temperatures is presented in figure 5, where the numerical profile has been included.

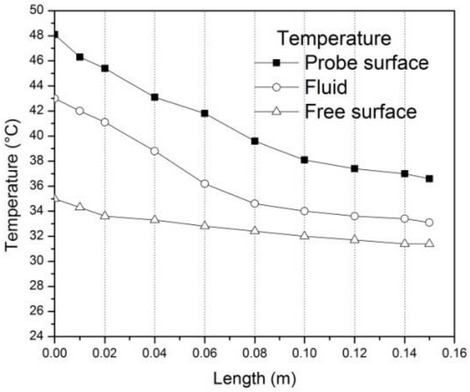

Figure 2. Experimental temperatures.

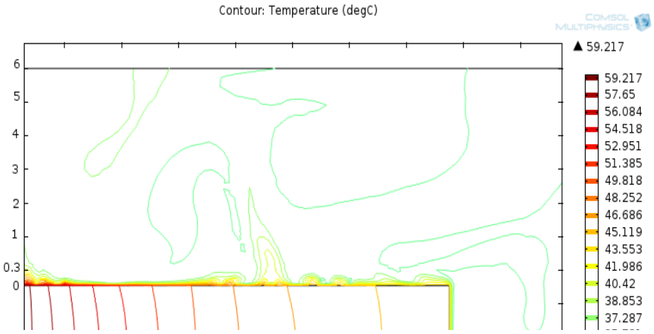

Figure 3. Numerical temperatures.

The numerical velocity distribution generated in the bulk of the fluid due to the convection is shown in figure 4. It is observed that there are five places where the velocity is maximum with a value near 0.02 m/s; between these places some swirls in which the velocity is slower, with values near to 0.01 m/s, and finally, in the rest of the fluid, the velocity is approximately 0.012 m/s.

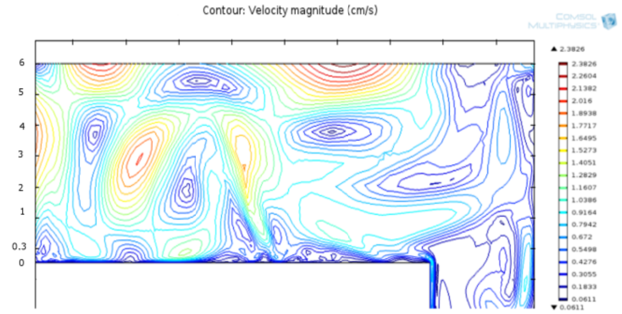

Figure 4. Velocity distribution.

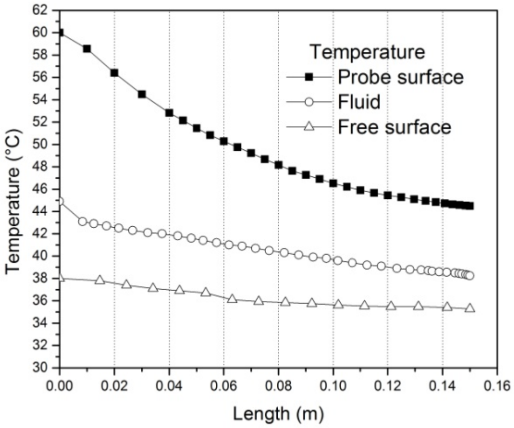

Figure 5. Numerical temperatures.

## CONCLUSIONS

The experimental results of the distributions of temperatures along a cylindrical short bar, heated by means of an electrical resistance, and submerged in water are presented. The supplied power was 500 W.

After 30 minutes, the maximum temperature value was registered at the initial extreme of the bar which was 48.3 °C; at a radial distance of 0.003 m it was 43.1 °C and at 0.05 m, 29.2°C. Near the final extreme of the bar, the measured values were 36.6, 33.0, and 25.2 °C respectively. The initial temperature of the fluid and the environment were constant at 20 °C.

Using the COMSOL multiphysics software a numerical simulation of the experiment was obtained. The numerical simulation of this problem resulted in slightly higher temperature values as compared with those experimental ones, except the temperatures in the bar, which were higher than those experimentally obtained. Further analyses of the method could lead to improve possible inaccuracies or failures. The velocities of the fluid as a result of the convection heat transfer could be also simulated.

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