ON THE CONVECTIVE HEAT TRANSFER FROM CIRCULAR CYLINDERS WITH APPLICATIONS TO HOT-WIRE ANEMOMETRY

A. Al-Salaymeh

Mechanical Engineering Department, Faculty of Engineering and Technology, The University of Jordan, Amman- Jordan Tel. +962 6 53 55 000 Ext. 2788, Fax: +96265355588

ABSTRACT

The present work includes an analysis of a single hot wire sensor to study the parametric effect on the accuracy of hot-wire anemometry. The time response of hot-wire has been studied and it is shown that the time constant is inversely proportional to the flow velocity. This study illustrates that non-uniform temperature distribution exists along a heated wire due to the effect of conduction heat losses and it ihas been found that the effect of conductive heat transfer rate through the prongs is negligible if the aspect ratio (l/d)is larger than 250. The maximum temperature occurs at the middle of the wire and it decreases mainly with increasing convective heat losses. To produce a uniform temperature distribution, high aspect ratios is recommended in order to reduce conduction heat losses and to get a uniform temperature distribution along the hot wire. In addition, the present work shows that the percentage of radiation from the total heat losses does not exceed 0.2% at low velocities and 0.1% at high velocities. Hence, the radiation term has been always neglected from the analysis of the hot-wire sensor.

Key words: hot-wire anemometer, convective heat transfer, circular cylinder

NOMENCLATURE

A_w	Cross-sectional area of the wire
C_w	Specific heat of the wire material
d_w	Wire diameter
h	Coefficient of convective heat transfer
I	Electrical current
k	Thermal conductivity
Nu	Nusselt number
Re	Reynolds number
t	Time
T	Temperature
U	Flow velocity
α	Temperature coefficient of resistance
ε	Emissivity of the hot-wire
ρ	*D*ensity
σ	Steven Boltzmann constant
ν	Kinematic viscosity
χ	Resistevity of the wire material

1. INTRODUCTION

There are many engineering applications in fluid mechanics which require air velocity to be measured, especially at very low speeds, for example the flow in a clean room and the heat transfer in the confined space of computer. Owing to their extremely low velocities and their variable temperature, it is necessary to look for a flow sensor, which is able to measure free convection speeds and is not strongly affected by ambient temperature.

The miniaturization of electronic components and the resulting increase in the power density have brought about changes in electronic packaging designs and have made understanding the characteristics of low-velocity airflow important. It is particularly difficult for compact electronics to achieve a reliable heat dissipation rate when the limited internal space is densely packed with sub-systems that pose a hindrance to the free circulation of cooling air.

HWA refers to hot wire anemometry techniques that measures the velocity and temperature of the flow, concentration changes in gas mixtures, and phase changes in multiphase flows based on convective heat transfer from a heated wire or film element placed in a fluid flow. The name of hot wire anemometer implies using a heated wire to make velocity measurements in air only. The word anemometer is inaccurate because the instrument is used in a variety of fluids such as water, polymer solutions, blood, mercury, oil and Freon. Also, the term hot wire is misleading because probes using a heated metal film are popular. This nomenclature was adopted in the early 1900s, when hot wire probes were used in air measurements only. Times have changed but the name remains.

At sufficiently low Reynolds numbers, forced and free convection interact in a manner which has not yet been fully investigated. Since free and forced convection in a particular fluid depend primarily on the Grashof and Reynolds numbers, respectively, a criterion for mixed flow involving only these two parameters should exist. The characteristic point of the mixed flow regime has the practical significance that it defines the lowest Reynolds number at which the heated wire in question can be used as an anemometer without ambiguity.

Practical sensors should meet the requirements of low cost, reliability, small size, low weight and easy handling. The importance of a practical flow sensor, which is able to measure an extremely low velocity, with a low cost is the

main motivation for the present study. Also, the proposed study aims to investigate the laminar flow and heat transfer around a heated circular cylinder at low Reynolds numbers under steady and unsteady conditions with applications to the hot-wire anemometry. The dominance of free convection over forced convection becomes more important as the flow velocity becomes lower, and therefore the mixed convection of heat transfer should be taken in the calculations. The knowledge gained from the detailed analytical and numerical investigations will allow a physical understanding of the sensor's properties and can result in a first sensor design. The aim of this study is to investigate hot wire sensors characteristics taking into consideration all kinds of heat transfer such as convection, conduction and radiation.Up to our knowledge, such investigation has not been done yet.

2. EXISTING KNOWLEDGE ON THE HWA

Measurements of heat losses from long cylinders located in free flows have been extensively carried out by various researchers, e.g. [1], since the 1914 work of King [2]. Heat-transfer laws for infinitely long cylinders are often used to predict the behaviour of heated wires and films, the length-to-diameter ratio being almost always large enough for this to be a good local approximation. These laws are usually expressed in non-dimensional form by giving the Nusselt number as a function of Reynolds number. One of the first heat-transfer laws was due to, and bears the name, of King [2]. King's derivation was based on the assumption of potential flow around the cylinder, which has been shown to provide a poor approximation of real flows. King presented his results in terms of heat transfer coefficients, one year before Nusselt [3] suggested a more general presentation, using a non-dimensional number, which is nowadays referred to by his name, to correlate heat-transfer data. Subsequent investigators presented their measurements in the form of Nu (Re) diagrams, e.g. [4].

The early analytical work of the flow around a circular cylinder at low Reynolds number was carried out in 1851 by Stokes [5]. Cole and Roshko [6] studied analytically the heat transfer from a circular cylinder in cross-flow based on Oseen's approximation for the flow field. Collis and Williams [4] indicated that even for large aspect ratios, the Cole and Roshko result overestimated the Nusselt number. Bradbury and Castro [7] described some measurements of heat transfer and convective time constants for fine wires. They showed that the relationship of Collis and Williams is a more representative expression for a wide range of wire temperatures.

Fand and Keswani [8] corrected Hilpert's data for heat transfer from cylinders to air in a cross-flow. The data were corrected to compensate for the influence of the temperature dependence of the fluid properties. Kassoy [9] was interested in the effects of variable fluid properties on low Reynolds number flow phenomena. Kassoy's experiments indicated that the relationship between the Nusselt number and the Reynolds number is very different from the expected values predicted by King's law.

Thom [10] presented in 1933 the first numerical study of the flow around a circular cylinder at Reynolds numbers of 10 and 20. Dennis et al. [11] investigated the steady laminar forced convection from a circular cylinder in a stream of viscous, incompressible flow at low Reynolds numbers. They calculated the mean and local Nusselt numbers and

compared them with available experimental data. Some discrepancies were found between the experimental data and the available theoretical solution based on Oseen's approximation. Sundén [12] studied the effect of viscous heating in forced convective heat transfer across a circular cylinder at low Reynolds numbers.

Lange [13] predicted numerically the heat and momentum transfer from a cylinder in a cross-flow with implications for hot-wire anemometry. He investigated the influence of the proximity of a highly conducting and an insulating wall on the heat transfer from a fine wire. Schmidt and Wenner [14] studied the heat transfer from the surface of a heated cylinder at high Reynolds numbers. Hatton et al. [15] performed an experiment to investigate combined forced and natural convection with a low-speed air flow over horizontal cylinders. They found that it would be difficult to construct a hot-wire anemometer for measuring very low speeds. Tamada et al. [16] studied analytically a two-dimensional flow past a cylindrical body at low Reynolds numbers. Hieber and Gebhart [17] made an analysis to study the forced heat convection from a circular cylinder at low Reynolds numbers. They neglected the natural convection and viscous dissipation and they assumed that the fluid is of constant properties. Wood [18] calculated the heat transfer from a fine hot wire at low Reynolds numbers. He determined two additional terms in Oseen's equation of the velocity and temperature field.

The appearance of commercial constant current anemometers, and later of commercial constant temperature anemometers, coincides with a major growth in popularity of the hot-wire instruments. Today the hot wire anemometer is used in research laboratories through out the world. There are many studies in the literature which have been contributed in development the hot wire anemometer and they are considered as excellent references. Some examples of the most convenient researches by Hinze [1], Bradshaw [20], Bruun [21], Perry [22] and Lomas [23].

3. THEORETICAL INVESTIGATIONS

The topic of hot wire anemometry (HWA) has been thoroughly looked upon aeronautic, chemical and mechanical engineers for the last century. HWA is based on convective heat transfer from a heated wire or film element placed in a fluid flow. The heat is generated inside the hot wire due to the wire resistance when the electrical current passes through it. The wire will experience heat losses by convection, conduction, and radiation depending on the flow conditions. The conduction and radiation have a small effect on the heat losses for the wire but the major effect is for the convection. The convection heat losses are a function of the flow conditions. Any change in the flow velocity will affect the coefficient of heat transfer and consequently the temperature of the wire, which also affects the wire resistance.

Figure 1 shows a schematic diagram of a hot wire anemometer. The sensor of the typical hot-wire probe is a wire, usually made of tungsten or platinum, about 1 mm long and 5 μm in diameter. The sensor is attached between the tips of two support needles by arc welding or soldering, and is electrically heated. The needles are usually made of materials that have low thermal conductivity. Its convection cooled by the fluid passing over it, and this cooling effect is

a measure of the fluid velocity. The probe body is usually made of epoxy of ceramic material of fabricated from a metal tube potted with epoxy. An electrical connecter is often located at the other end of the probe body to allow easy removal and replacement of the probe. The contacts of the connector are sometimes plated with gold to reduce resistance, and the connector is usually designed to be watertight.
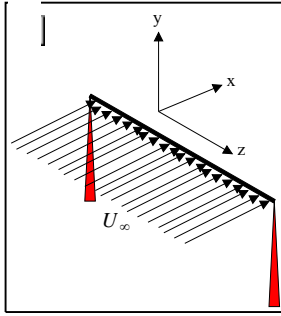

Figure 1: A schematic diagram of the hot wire anemometer.

The heat transfer from a heated wire placed in fluid flow depends on the properties of the ambient fluid (e.g. density, viscosity, thermal conductivity and specific heat) and parameters of the flow (e.g. velocity vector, fluid temperature and pressure). The heat transfer from the heated wire takes place by convection, conduction and radiation. More details about the theoretical approach can be found in Al-Salaymeh and Durst [24].

To analyze the energy balance for the heated wire, we look at the differential element composed of small length of the heated wire. This differential element has length dx and cross-sectional area A_w. The heat, which is generated electrically in this small differential element, is dissipated by convection to the fluid, by radiation to the surroundings and by conduction to the parts of the wire to which the differential element is attached. In addition, there is heat storage in the differential element of wire. These effects are expressed mathematically, so that the thermal energy balance for an incremental heated wire element can be expressed as

$$d\dot{Q}_e = d\dot{Q}_{fc} + d\dot{Q}_c + d\dot{Q}_r + d\dot{Q}_s \tag{1}$$

where $d\dot{Q}_e$ is the electrical heat-generation rate, $d\dot{Q}_{fc}$ is the forced convective heat transfer, $d\dot{Q}_c$ is the conductive heat-transfer rate, $d\dot{Q}_r$ is the radiation heat-transfer rate, and $d\dot{Q}_s$ is the heat storage rate.

By inserting equations for each term in equation (1), then an energy balance yields the following differential equations for the heat balance in the heated wire:

$$\frac{I^2 \chi_w}{A_w} + k_w A_w \frac{\partial^2 T_w}{\partial x^2} - \pi d_w h(T_w - T_a) - \pi d_w \sigma \varepsilon (T_w^4 - T_s^4)$$
$$- \rho_w c_w A_w \frac{\partial T_w}{\partial t} = 0 \tag{2}$$

where I is the heating current, χ_w is the resistivity of the heated wire material at the local wire temperature T_w, A_w is the cross-sectional area of the wire, dx is the differential

element for the heated wire, d_w is the heated diameter, h is the coefficient of convective heat transfer, T_w is the heated wire temperature, T_a is the temperature of the fluid, k_w is the coefficient for the thermal conductivity for the heated wire, x is the distance measured along the heated wire, σ is the Stefan-Boltzmann constant, ε is the emissivity of the heated wire, T_s is the temperature of the surroundings, ρ_w is the density of the wire material, c_w is the specific heat of the wire material and t is the time.

It is common for the heat transfer coefficient to be expressed in terms of the Nusselt number, Nu, which defined as

$$Nu = h d_w / k_f \tag{3}$$

Where h is the convective heat transfer coefficient and k_f is the thermal conductivity of the fluid. The heat transfer law for a heated wire can be expressed, as Collis and Williams [1959] found, in the form

$$Nu \left[\frac{T_f}{T_a} \right]^{-0.17} = 0.24 + 0.56 \, Re^{0.45} \tag{4}$$

Where Re is Reynolds number of the flow, which can be calculated as

$$Re = u d_w / \nu \tag{5}$$

Where u is the flow velocity and ν is the kinematic viscosity of the fluid at ambient temperature. The fluid properties should be calculated at the film temperature, which can be defined as

$$T_f = (T_w + T_a)/2 \tag{6}$$

The temperature dependence of the resistivity for the heated wire material, χ_w, can be expressed in the form

$$\chi_w = \chi_a + \chi_0 \alpha_0 (T_w - T_a) \tag{7}$$

where χ_0 and χ_a are the resistivity values of the wire at the ambient fluid temperature at $0°\,C$ and T_a respectively and and α_0 is the temperature coefficient of resistivity at $0°\,C$.

After substituting equations (3) and (7) into equation (2), then the thermal energy balance for a heated wire can be rewritten as:

$$\frac{I^2}{A_w} \{ \chi_a + \chi_0 \alpha_0 (T_w - T_a) \} + k_w A_w \frac{\partial^2 T_w}{\partial x^2} - \pi Nu \, k_f (T_w - T_a)$$
$$- \pi d_w \sigma \varepsilon (T_w^4 - T_s^4) - \rho_w c_w A_w \frac{\partial T_w}{\partial t} = 0 \tag{8}$$

4. RESULTS AND DISCUSSION

The response of the hot wire will be studied at the maximum temperature, hence the conduction term will not be considered. Therefore, the thermal energy balance for a heated wire with negligible conduction can be drawn from equation (8) as:

$$\frac{dT_w}{dt} = \frac{I^2 \chi_a}{A_w(\rho_w c_w A_w)} + \left\{ \frac{I^2 \chi_a \alpha}{A_w(\rho_w c_w A_w)} - \frac{\pi k_f}{\rho_w c_w A_w} \right\}$$

$$\left(\left(0.24 + 0.56 \, \mathrm{Re}^{0.45} \left[\frac{T_f}{T_a} \right]^{-0.17} \right) \right) (T_w - T_a) + \frac{\pi d \sigma \varepsilon}{\rho_w c_w A_w} (T_w^4 - T_a^4) \quad (9)$$

The Collis and Williams equation for Nusselt number has been substituted into equation (8) to express the temperature of the heated wire as a function of the Reynolds number. Equation (9) which is an ordinary differential equation has been solved numerically for different flow conditions. Runge-Kutta Method has been used to find the variation of the maximum temperature with time. Figure 2 shows the variation of the maximum temperature of the heated wire as a function of time and at different flow velocities.
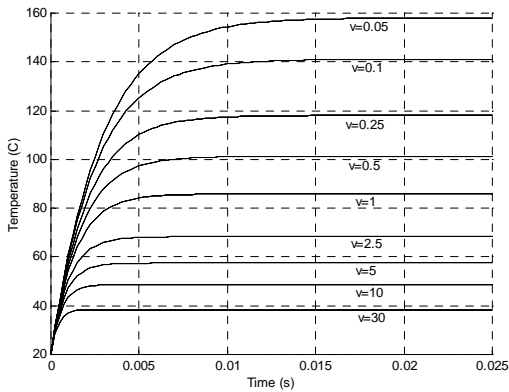

Fig 2: Temperature variations of the heated wire as a function of time at different flow velocities

The convection heat transfer rate increases with increasing the flow velocity and this is clear from the dependence of the Nusselt number on the Reynolds number. The maximum temperature of the heated wire is a function of the flow velocity as shown in figure 3. The sensitivity of the hot wire decreases with increasing velocity and the relationship between the output voltage of the hot-wire sensor and the flow velocity is non linear. Therefore, the sensitivity of the hot wire is high at low velocities and it is low at very high flow velocities as shown in figure 3.

The dynamic response characteristics of the heated wire are amongst the most difficult to measure directly. Consequently, even now, a full understanding of these characteristics cannot be claimed. Many of the more dominant ones are well documented in the literature, e.g. [25-26]. To obtain the wire response, we must solve time-dependent equations of heat conduction taking account of thermal inertias. The sensor is considered to be a cylinder of infinite length at uniform temperature, i.e. end conduction losses and radial temperature gradients are neglected. Also, all heat transfer is assumed to be by forced convection. With the above assumptions, the thermal response equation is the first order and non homogeneous differential equation.

Figure 4 shows that the time constant of the hot wire decreases with increasing velocity in the case the other parameters such as wire diameter and heating current is fixed. The response of the hot wire is fast and it is clear from Figure 4 that at higher velocities the steady state will be achieved faster than cases in lower velocities. Figure 4 presents the variation of the time constant with flow velocity. This figure implies that at higher velocities the time constant

becomes lower, which means that the wire reaches its maximum and steady state quickly. It can be explained that at higher velocities the maximum temperature is closer to the ambient temperature, thus the time needed to approach it is less than cases in lower velocities.
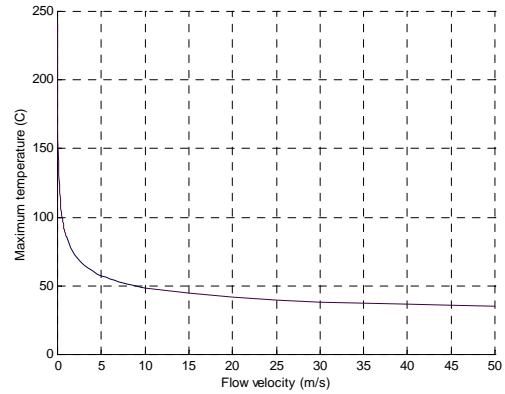

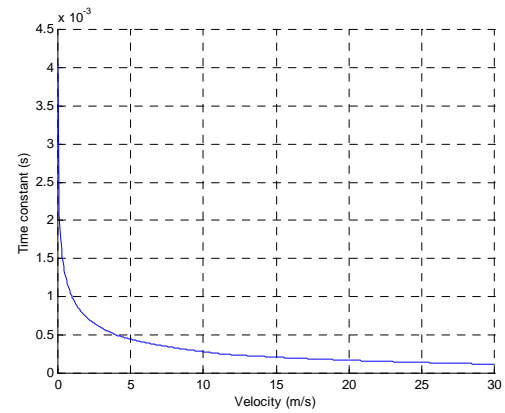Fig. 3: Maximum temperature variations as a function of flow velocities

Fig. 4: Time constant of hot wire as a function of the flow velocity

Most researches neglects the radiation term in the heat balance equation due to its small effect in the total heat transfer rate of the hot wire. The percentage of the radiation term from the total heat transfer rate has been investigated. To study the radiation effect, the radiation term in equation 9 will be omitted. Thus equation 9 becomes:

$$\frac{dT_w}{dt} = \frac{I^2 \chi_a}{A_w(\rho_w c_w A_w)} + \left\{ \frac{I^2 \chi_a \alpha}{A_w(\rho_w c_w A_w)} - \frac{\pi k_f}{\rho_w c_w A_w} \right\}$$

$$\left(\left(0.24 + 0.56 \, \mathrm{Re}^{0.45} \left[\frac{T_f}{T_a} \right]^{-0.17} \right) \right) (T_w - T_a) \quad (10)$$

Solving this equation numerically, the same procedure done in solving equation 9, the maximum temperature variation with time including the radiation term is compared to the maximum temperature variation with time without radiation. Figure 5 shows the difference in temperature values for the two cases at low velocities. From figure 5 it can be concluded that the radiation heat transfer increases at low velocities, due to higher maximum temperature. But, radiation is still not considered as an affecting value from the total heat transfer rate. The effect of radiation term on the total heat transfer rate and hence on the maximum temperature is very small. The percentage of radiation from the total heat transfer for the wire is < 0.2% in low velocity region (< 1 m/s), and < 0.01% in the high velocity region.

The heat transfer from a hot-wire probe containing a finite aspect ratio sensor deviates from the prongs, or the active part of the wire may be removed from the prongs by a plating technique. In comparison with the wire element, the prongs are massive, and the prong temperature T_p, will therefore remain at a temperature close to the time-mean ambient fluid temperature T_a. Since the wire is operated at an elevated temperature, conductive heat transfer will take place towards the prongs, resulting in a temperature distribution within the wire element, which can be determined from the heat-rate balance equation for an incremental wire element.
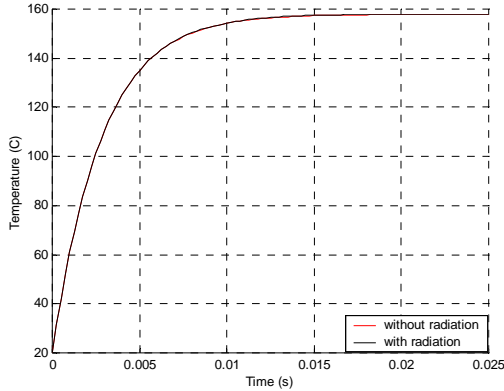

Fig. 5: Temperature Variation in Time with and without Radiation at Low Velocity

Under steady state conditions $\partial T_w / \partial t = 0$, and by neglecting the radiation heat-transfer rate and applying the steady state conditions, therefore equation (8) can be rewritten as:

$$k_w A_w \frac{\partial^2 T_w}{\partial x^2} + \left[\frac{I^2 \chi_0 \alpha_0}{A_w} - \pi d_w h \right] (T_w - T_a) + \frac{I^2 \chi_a}{A_w} = 0 \qquad (11)$$

Since the fluid temperature T_a is constant along the wire, equation (11) has the following form:

$$\frac{d^2 T_1}{dx^2} + K_1 T_1 + K_2 = 0 \qquad (12)$$

where $T_1 = T_w - T_a$; $K_1 = \dfrac{I^2 \chi_0 \alpha_0}{k_w A_w^2} - \dfrac{\pi d h}{k_w A_w}$ and $K_2 = \dfrac{I^2 \chi_a}{k_w A_w^2}$

Equation (12) is a second order partial differential equation with one variable; it can be solved numerically using finite element method. The second derivative can be written as:

$$f''(x_i) = \frac{f(x_{i+2}) - 2 f(x_{i+1}) + f(x_i)}{\Delta z^2} \qquad (13)$$

Then, equation (11) can be rewritten as:

$$\frac{I^2 \chi_w \Delta z^2}{k_w A_w^2} + \left(1 - \frac{\pi d_w h \Delta z^2}{k_w A_w}\right) T_i + \frac{\pi d_w h \Delta z^2}{k_w A_w} T_\alpha + T_{i+2} - 2 T_{i+1} = 0 \qquad (14)$$

Equation (14) has the form:

$$T_{i+2} - 2 T_{i+1} + (1 - A) T_i + B = 0 \qquad (15)$$

where, $A = \dfrac{\pi d_w h \Delta z^2}{k_w A_w}$ and $B = \dfrac{I^2 \chi_w \Delta z^2}{k_w A_w^2} + \dfrac{\pi d_w h \Delta z^2}{k_w A_w} T_\alpha$

and the two boundary conditions are:

$T(x=L/2) = T_{max}$
$T(x=L) = T(x=0) = T_p$

Equation (14) can be written in matrix form as:

$$\begin{bmatrix} -2 & 1 & 0 & 0 & 0 \\ (1-A) & -2 & 1 & 0 & 0 \\ 0 & (1-A) & -2 & 1 & 0 \\ 0 & 0 & (1-A) & -2 & 1 \\ 0 & 0 & 0 & (1-A) & -2 \end{bmatrix} \begin{bmatrix} T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} = \begin{bmatrix} -B - (1-A) T_p \\ -B \\ -B \\ -B \\ -B - T_{max} \end{bmatrix} \quad (16)$$

The conductive heat loss $\dot{Q}_{cp}$ to the two prongs can be calculated from the temperature gradient. The temperature gradient at the end of the wires has been determined for each flow velocity from Figure 6. The temperature distribution $T_w(x)$ can be compared with the temperature $T_{w,\infty}$ of a similar infinitely long wire.

The variation in the temperature profile, in the form of dimensionless temperature ratio $(T_{w,max} - T_a)/(T_{w,m} - T_a)$ as a function of dimensionless wire length (x/l), is shown in figure 7. The maximum temperature occurs at the middle of the wire length where x=0. For various aspect ratio of hot wire, Figure 7 shows the variation of the temperature along the wire. Figure 7 shows also a very good agreement between the present results about the temperature distributions along the heated wire and the previous work which has been carried out by Davies and Fisher [27]. By increasing the aspect ratio (l/d), the effect of the conduction term decreases.
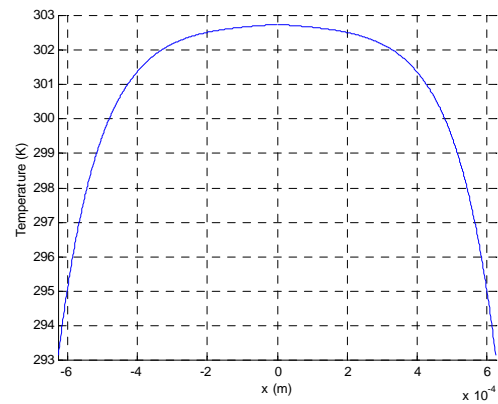

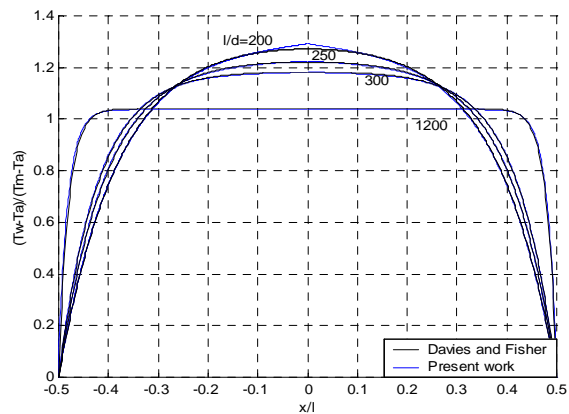
Fig. 6: Temperature distribution along the heated wire

Fig. 7: A comparison of the present results for temperature distributions along the hot wire for different aspect ratios and the results of Davies and Fisher [27].

5. CONCLUSIONS

The response of the hot wire is affected by the variations of the flow conditions and consequently the changes in the heat transfer rates. Studying the temperature distribution allows for the understanding of the heat transfer rate changes and the parameters that affects it. These parameters have been examined in the present study. The present paper has mainly discussed the time response of the hot wire, temperature distribution along the hot wire, and the effect of convection, conduction, and radiation on the temperature distribution along the hot wire.

The heat conduction to the support needles is negligible, especially if the aspect ratio which is the length to the diameter ratio is large. The heat radiation from the the heated sensor to the cooler surrounding is very small and often is neglected in calculations. Under normal operating conditions, the radiation losses are much less than 0.1% of the convection losses and hence will not be considered further. The heat stored in the heated sensor is not negligible even for thin wires having small mass. For a tungsten probe, the overheat ratio is usually set to a value of less than 2, with 1.8 being the recommended value. A high wire temperature should be selected in order to achieve high velocity sensitivity. To avoid oxidation it is essential that the wire temperature at any point along the wire element be kept well below $350^{\circ}C$.

6. REFERNCES

[1]   Norberg, C. (1994). An Experimental Investigation of the Flow Around a Circular Cylinder: Influence of Aspect Ratio. J. Fluid Mech., 258, 287-316.

[2]   King, L. V. (1914). On the Convection of Heat from Small Cylinders in a Stream of Fluid: Determination of the Convection Constants of Small Platinum Wires with Applications to Hot-Wire Anemometry. Phil. Trans. Roy. Soc. (London), A, 214, 373-432.

[3]   Nusselt, W. (1915). Das Grundgesetz des Wärmeüberganges. Gesund.-Ing., 38(42), 477-482.

[4]   Collis, D. C. and Williams, M. J. (1959). Two-Dimensional Convection from Heated Wires at Low Reynolds Numbers. J. Fluid Mech., 6, 357-384.

[5]   Stokes, G. G. (1851). On the Effect of the Internal Friction of Fluids on the Motion of Pendulums. Trans. Camb. Phil. Soc., 9(2), 8-106.

[6]   Cole, J. and Roshko, A. (1954). Heat Transfer from Wires at Reynolds Numbers in the Oseen Range. Proc. Heat Transfer and Fluid Mech. Inst., 6, 357-384, 1954. University of California, Berkeley, CA.

[7]   Bradbury, L. J. S. and Castro, I. P. (1972). Some Comments on Heat-Transfer Laws for Fine Wires. J. Fluid Mech., 51, 487-495.

[8]   Fand, R. M. and Keswani, K. K. (1973). Recalculation of Hilpert's Constants. J. Heat Transfer, Trans. ASME, 95, 224-226.

[9]   Kassoy, D. R. (1967). Heat Transfer from Circular Cylinders at Low Reynolds Numbers. I. Theory for Variable Property Flow. Phys. Fluids, 10(5), 938-946.

[10]   Thom, A. (1933). The Flow Past Circular Cylinders at Low Speed. Proc. Roy. Soc. London A, 141, 651-669.

[11]   Dennis, S. C. R., Hudson, J. D., and Smith N. (1968). Steady Laminar Forced Convection from a Circular Cylinder at Low Reynolds Numbers. Phys. Fluids, 11(5), 933-940.

[12]   Sundén, B. (1992). Viscous Heating in Forced Convective Heat Transfer Across a Circular Cylinder at Low Reynolds Number. Int. J. Num. Methods Eng., 35, 729-736.

[13]   Lange, C. F., Durst, F., and Breuer, M. (1998). Momentum and Heat Transfer from Cylinders in Crossflow at $10^{-4} \leq \mathrm{Re} \leq 200$. Int. J. Heat Mass Transfer, 41, 3409-3430.

[14]   Schmidt, E. and Wenner, K. (1941). Wärmeabgabe über den Umfang eines angeblaseneen geheizten Zylinders. Forsch. G. Ing., 12(2), 65-73.

[15]   Hatton, A. P., James, D. D., and Swire, H. W. (1970). Combined Forced and Natural Convection with Low-Speed Air Flow Over Horizontal Cylinders. J. Fluid Mech., 42, 17-31.

[16]   Tamada, K., Miura, H., and Miyagi, T. (1983). Low-Reynolds-Number Flow Past a Cylindrical Body. J. Fluid Mech., 132, 445-455.

[17]   Hieber, C. A. and Gebhart, B. (1968). Low Reynolds Number Heat Transfer from a Circular Cylinder. J. Fluid Mech., 32, 21-28.

[18]   Wood, W. W. (1968). Calculation for Anemometry with Fine Hot Wires. J. Fluid Mech., 32, 9-19.

[19]   Hinze, J.O. (1975). *Turbulence*, 2nd edn. McGraw-Hill, New York.

[20]   Bradshaw, P. (1971). *An Introduction to Turbulence and Its Measurement*. Pergamon Press, Oxford, U.K.

[21]   Bruun, H. H. (1995). *Hot-Wire Anemometry. Principles and Signal Analysis*. Oxford University Press, Oxford, U.K.

[22]   Perry, A. E. (1982). *Hot-Wire Anemometry*. Oxford University Press, Oxford, U.K.

[23]   Lomas, C. G. (1986). *Fundamentals of Hot Wire Anemometry*. Cambridge University Press, Cambridge.

[24]   Al-Salaymeh, A. and Durst, F. (2004) Development and Testing of a Novel Single-Wire Sensor for Wide Range Flow Velocity Measurements, Meas. Sci. Technol. 15, 1-12.

[25]   Antonia, R. A., Browne, L. W. B., and Chambers, A. J. (1981). Determination of Time Constants of Cold Wires. Rev. Sci. Instrum., 52, 1382-1385.

[26]   Graham, L. J. W. and Bremhorst, K. (1991). Instantaneous Time-Constant Adjustment of Cold-Wires Acting as Resistance Thermometers when Using Multi-Wire Anemometer Probes. Meas. Sci. Technol., 2, 238-241.

[27]   Davies, P. O. and Fisher, M. J. (1964). Heat Transfer from electrically heated cylinders. *Proc. Roy. Soc.*, A280, 486-527.