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Natural Convection Heat Transfer from an Inclined Cylinder to Glycerol and Water

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Abstract. Free convection heat transfer from the outside surface of an inclined cylinder for water and glycerol was experimentally investigated at different heat flux. For all test fluids, experimental results show that average Nusselt number decreases with increasing inclination of the cylinder to the horizontal at constant heat flux. A new model for the prediction of average Nusselt number, in free convection from the outside surface of an inclined cylinder is proposed, which predicts the experimental data with a satisfactory accuracy. Since there is little research on natural convection from inclined cylinders, the present research work is an attempt to fill a part of this existing gap.

Keywords: Natural convection, inclined cylinder, glycerol, water, heat transfer

1. Introduction

Natural convection from the outside surface of cylinder is employed for heating and cooling in many industrial processes such as high voltage power transmission lines, solar collectors, electronic devices, nuclear safety systems, and refrigeration condensers. Many investigations were carried out on natural convection heat transfer from the outside surface of vertical and horizontal cylinders in both the constant temperature and the constant heat flux conditions. Özgür Atayilmaz [1] and also Özgür Atayilmaz and Teke [2] have a wide-ranging survey on some correlations in this field. The data on natural convection from inclined cylinders are, however, very limited [3]-[6].

Lia and Tarasuk [7] used the cylinder diameter (D) and inclination angle (φ), and proposed the correlation $\mathrm{Nu_D} = \mathrm{m}(\varphi)\mathrm{Ra_D^{n(\varphi)}}$. Al-Arabi and Khamis [6] used the cylinder length L and inclination angle (φ), and proposed the correlation $\mathrm{Nu_L} = \mathrm{m}(\varphi)\mathrm{Ra_L^{n(\varphi)}}$ where m and n vary depending on the angle of inclination. Farber and Rennat [8], experimented with a stainless steel tube 1.829 m long and 0.003175 m OD heated by passing an electric current through it to give a constant heat flux. Khamis [9], experimented with steam heated (constant temperature) brass tubes of different lengths and diameters. Oosthuizen [10] experimented with aluminium cylinders. The diameters varied between 19.1 and 25.4 mm, the length between 152.4 and 304.8 mm and the angle of inclination to the horizontal between 0° to 90°. Table I summarizes the natural convection heat transfer correlations for inclined cylinders. The present research work was carried out to fill a part of the existing gap. It is concerned mainly with the study of the effect of the angle of inclination on natural convection heat transfer from the outside surface of a cylinder.

2. Experimental Setup

Fig. 1 schematically demonstrates the experimental equipment used in the present investigation. The cubic shaped vessel is made of stainless steel containing approximately 20 L of test liquid. System is continuously monitored and regulated to preserve predetermined operating conditions. A PC-based data

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acquisition system was used to record some of the measuring parameters. The whole system is heavily insulated for more controllability and reduction of heat loss. The vessel is equipped with two heaters: 1) auxiliary heater, which is a simple element to rise and maintain the bulk temperature to any set point, and 2) rod heater, which consists of an internally heated stainless steel rod (OD: 22 mm, heating length: 130 mm) equipped with four thermocouples stainless steel shielded and embedded along the circumference of the rod, very close to the heating surface. To minimize thermal contact resistance between each thermocouple and sheath, silicon paste is injected into the location of placing each thermocouple. Also, to minimize the influence of surface roughness on heat transfer, the surface of the cylinder was polished using emery paper with an average roughness of 400 µm. The rod heater operates with variable A/C electrical power input providing variable heat fluxes. The electrical input power of the rod heater was calculated by the product of electrical voltage, current and cosine of the difference between input electrical voltage and current.

Table 1: Heat Transfer Correlations for Inclined Cylinders

Reference	Correlation	L/D	Pr	φ
Sedahmed and Shemilt [11]	$Nu_L = 0.498(Ra_L \cos\varphi)^{0.28}$ $1.9 * 10^{10} < Ra_L \cos\varphi < 3.8 * 10^{11}$	4.65 ~14.3	2300	Inclined
Al-Arabi and Salman[5]	$Nu_L = [0.6 - 0.488(\sin(90-\varphi))^{1.73}](Ra_L)^{1/4+1/12(\sin(90-\varphi))^{1.73}}$ $10^{5.5} < Ra_L < 10^7$	25	0.7	Inclined
Oosthuizen [10]	$\frac{Nu_D}{(Gr_D \cos\varphi)^{1/4}} = 0.42\left[1+\left(\frac{1}{31}/\bar{L}^{1/4}\right)^3\right]^{1/2}$ $\bar{L} = \frac{L}{D\tan\varphi}$ $10^4 < Ra_D < 10^9$	8,10,16	0.7	Inclined
Stewart and Buck [12]	$\frac{Nu_D}{(Ra_D \cos\varphi)^{1/4}} = 0.48 + 0.555\left(\left(\frac{D}{L\cos\varphi}\right)^{1/4} + \left(\frac{D}{L}\right)^{1/4}\right)$ $4 * 10^4 < Ra_D < 4 * 10^8$	6,9,12	0.7	Inclined
Stewart [13]	$\frac{Nu_D}{(Ra_D \cos\varphi)^{1/4}} = 0.53 + 0.555\left(\left(\frac{D}{L\cos\varphi}\right)^{1/4} - \left(\frac{D}{L}\right)^{1/4}\right)$ $10^4 < Ra_D < 10^8$	6~12	0.7	Inclined

The temperature drop due to the existence of small distance between surface and thermocouple location was calculated by applying heat conduction equation for cylinders:

$$1/r \;\; d/dr\,(kr\,dT/dr) = 0 \tag{1}$$

In (1), k is the temperature dependent thermal conductivity of the heater, which was approximated to a linear function of temperature. The heat transfer coefficient was calculated simply by Newton's cooling law and known value of wall temperature. In addition, to change the angle of the cylinder of a hydraulic jack is used. Potentially, there are various sources of errors through measurements, which are summarized in Table II. The range of operating conditions used in this investigation and some selected physical properties are presented at Table III. All the physical properties of the fluids prepared from authentic handbooks [14], [15]

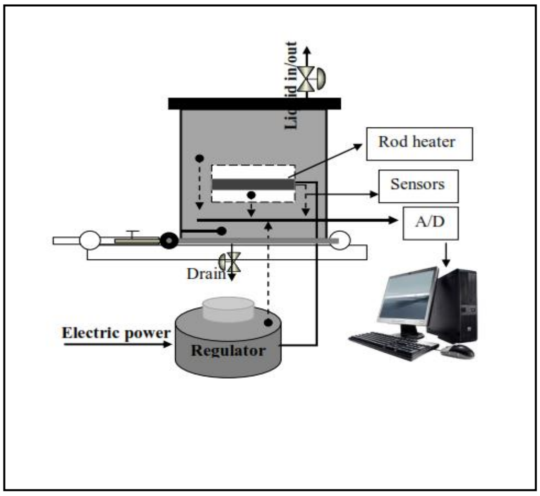


Fig. 1: Scheme of experimental apparatus used in this investigation

Table 2: Uncertainties of the Measurement Instruments

Parameter	Instrument	Uncertainty
Surface temperature (K)	K-type thermocouple	0.2 K
Voltage (V)	Mastech MS8205C multi-meter	±1 V
Current (I)	Mastech MS8205C multi-meter	±0.1 A
Bulk temperature (K)	Pt-100 thermo-resistance	±0.1 K
Heat flux (Wm^{-2})		±3.32%

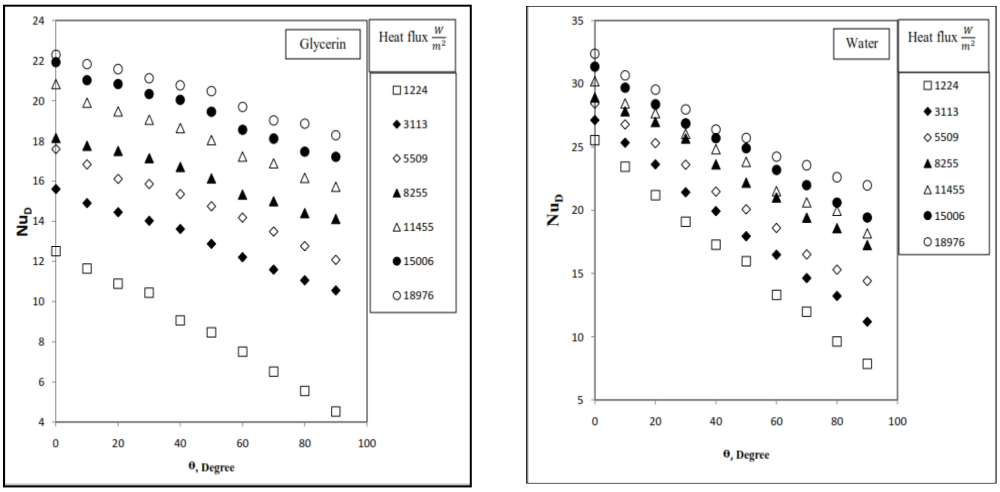
Table 3: Operating Parameters and Physical Properties

Range of operating parameters					
Heat Flux	5 – 20 kWm^{-2}	Bulk temperature		50°C	
Physical properties at $\mathbf{P = 101325\ Pa}$					
System	ρ_l (kgm^{-3})	k_l ($Wm^{-1}K^{-1}$)	μ_l (Pa.s)	c_{pl} ($Jkg^{-1}K^{-1}$)	
Water	981-988	0.637-0.653	0.00044-0.00056	4175-4183	
Glycerol	1212-1237	0.288-0.31	0.023-0.019	2516-2656	

3. Results and Discussion

A total of 141 test runs were conducted in the present study covering the following ranges and values: $Gr_D = 1.7*10^6 - 5*10^7$ (water), $Gr_D = 270 - 6.7*10^4$ (glycerol), Pr = 2.71 – 3.64 (water), Pr = 198 – 1033 (glycerol), $Ra_D = 6.3*10^6 - 1.31*10^8$ (water), $Ra_D = 2.7*10^5 - 1.35*10^7$ (glycerol), φ = 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90°. All fluids properties were calculated at the film temperature given by $T_f = (T_s + T_b)/2$.

The effect of the inclination angle of the cylinder on the average Nusselt number for water and glycerol is shown in Fig. 2a and Fig. 2b, respectively, for the different heat fluxes.



(b) (a)

Fig. 2: Effect of inclination angle (φ=0: horizontal) on average Nusselt number. (a) water (b) glycerol

As shown in Fig. 2 for all test fluids, the average Nusselt number decreases as the inclination angle of the cylinder increases, at constant heat flux; however, experimental data show that average Nusselt number increases with increasing heat flux, at a fixed inclination of the cylinder. Furthermore, heat transfer coefficient of water is greater than that of glycerol. The comparison of the present work with those in the literature is not an easy work. The reason is that there is no work available in the literature which is similar to the present research in terms of geometrical shape of heater, working fluids and inclinations at the same time.

Table IV compares the performances of the major existing predictive correlations to the current experimental data.

Table 4: Compares the Major Existing Predictive Correlations to the Current Experimental Data

	Sedahmed and Shemilt [11]	Oosthuizen [10]	Stewart and Buck[12]	Stewart[13]
Water	90%	35%	Very off	Very off
Glycerol	31%	78%	Very off	Very off

Operating parameters such as cylinder diameter, cylinder length, working fluids and material of cylinder can be the causes of these deviations.

4. Empirical Correlations

According to the least square method, the experimental average Nusselt number can be correlated as:

$$Nu_D = 1.1(Ra_D)^{0.2-0.045\sin\varphi} \quad (2)$$

A point should be highlighted here that the preference of this correlation over the proposed correlations is that it can be generalized and used for different positions of a cylinder (horizontal, vertical and inclined at the same time), whereas the other correlations mainly only deal with one position of cylinder.

The average error of this correlation from the experimental data is found to be less than about 14%. The absolute error is defined by (3):

$$AAE\% = \left|\frac{Nu^{predicted}}{Nu^{experimental}} - 1\right| * 100 \quad (3)$$

5. Conclusion

Free convection heat transfer from an inclined cylinder has been investigated experimentally at different heat flux. It was found that: (i) for any inclination of the cylinder, the average Nusselt number increases with increasing heat flux, (ii) for any heat flux, the average Nusselt number decreases with increasing inclination of the cylinder, (iii) heat transfer coefficient of water is greater than that of glycerol at the same conditions. In this research, the proposed correlation for the prediction of average Nusselt number, in free convection from the outside surface of an inclined cylinder predicts the experimental data with a satisfactory accuracy. Although the obtained results of this research are different from those available in the previous investigations for inclined cylinders, the trends of changes in Nusselt number in different inclinations are consistent in the literature.

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Nomenclature:

Pr	Prandtl number
Gr	Grashof number
Ra	Rayleigh number
Nu	Nusselt number
D	Cylinder diameter
L	Cylinder length
P	Pressure (Pa)
k	Thermal conductivity ($Wm^{-1}K^{-1}$)
c_p	Specific heat at constant pressure (J kg-1K-1)
Greek symbols	
ρ	Density (kg m^{-3})
φ	Angle of inclination, degree ($\varphi = 0: Horizontal$)
β	Volume expansion coefficient ($m^3.K^{-1}$)
Δ	Difference
μ	Viscosity (Pa.s)
Subscripts	
l	Liquid
b	Bulk
f	Film
s	Surface
D	Cylinder diameter
L	Cylinder length