



Effect of cylinder Orientation on free convective heat transfer in glycerol

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ABSTRACT

The effect of cylinder orientation on the free convective heat transfer in glycerol is studied for the Rayleigh numbers, $10^{-6} \leq Ra \leq 10^9$ and Prandtl number, $Pr = 11630$. While varying the orientation of the cylinder, correlations due to Churchill & Chu, Raithby & Holland, Kuehn & Goldstein, Fand et al, Jaluria and Neeta et al are used to evaluate the free convective Nusselt number as a function of Rayleigh number at orientations of $0^\circ, 10^\circ, 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ, 70^\circ, 80^\circ$ and 90° . Additionally, the Rayleigh number is kept fixed at three regimes of $10^{-6}, 10^0$ and 10^6 and the free Nusselt number is evaluated as a function of the cylinder orientation. At maximum orientation ($\theta = 90^\circ$) an increase of 114% in Nusselt number is observed for Kuehn & Goldstein correlation.

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1. Introduction

Convective heat transfer is governed by the laws of fluid flow, the equation of continuity and the equation for the heat-flow in a moving fluid. An exact solution of these equations with particular boundary conditions is not feasible except in certain simple cases. However, important relationships may be obtained from these equations by means of the theory of similarity. Thus, for natural convection the Nusselt number should be a function of the Grashof number and the Prandtl number, that is

$$Nu = f(Gr, Pr)$$

The form $f(Gr, Pr)$ can be determined either strictly experimentally or by using theoretical analysis with some experimental information.

The theoretical description of heat transfer by convection requires knowledge of hydrodynamics principles and the heat conduction process. In principle, this topic can be described by the solutions of the following Navier-Stokes equations:

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho(\vec{v} \cdot \nabla) \vec{v} = \rho \vec{g} - \nabla p + \eta \nabla^2 \vec{v} + \frac{1}{3} \eta \nabla(\nabla \cdot \vec{v}) + \vec{F} \quad \dots (1)$$

$$\frac{\partial p}{\partial t} + \rho \nabla \cdot \vec{v} + v \cdot \nabla p = 0 \quad \dots (2)$$

$$c_p \rho \frac{\partial T}{\partial t} = \lambda \nabla^2 T + C_p \rho \vec{v} \cdot \nabla T \quad \dots (3)$$

These equations can only be solved with appropriate boundary conditions and equation of state. The physical quantities, \vec{v} represents the velocity, ρ the density, and T the temperature, all of which are spatial point (\vec{r}) functions and, in general, depend on time, t .

The quantity (\vec{g}) is the gravitational acceleration, η the viscosity, C_p the specific heat at constant pressure, and λ the thermal conductivity. The symbol \vec{F} represents all forces other than gravitational imposed on the fluid system. For example, if an uncharged fluid is exposed to an electric field, \vec{E} , then

$$\vec{F} = -\frac{1}{8\pi} E^2 \epsilon + \frac{1}{8\pi} \left[E^2 \left(\frac{\partial \epsilon}{\partial \rho} \right)_T \rho \right] \dots (4)$$

where ϵ is the dielectric constant given as

$$\epsilon = 1 + 4\pi\chi_\epsilon \quad \dots (5)$$

here, χ_ϵ is the electric susceptibility of the medium.

In practical applications of heat transfer it is customary to introduce the heat transfer coefficient h defined by

$$h = \frac{Q}{A\theta} \quad \dots (6)$$

where Q is the rate of heat transfer, A the area of the surface of the heated body, and

θ the temperature difference between the surface of the object and the main body of

the fluid.

Effectively h is a measure of heat transfer per unit area per unit time under unit temperature gradient. It includes the combined effects of conduction through the stagnant film and convection in the fluid. Experimentally, it has been found that h depends on the properties of the surface (shape, dimensions, temperature),

the fluid (density, specific heat, viscosity, heat conductivity, temperature) and the flow (type, direction, velocity).

1.1 Independent dimensionless numbers

Theoretical rigorous calculations of h from the fundamental principles have been all but impossible because of the obvious mathematical difficulties. However, the application of semi theoretical methods based on the theory of similarity (integral, differential, and dimensional methods) has given a multitude of important results and afforded some insight into the complex mechanism of convection processes. For example, this approach can be applied to the heat transfer due to free convection in a fluid from a regular body characterized by a linear dimension l (the diameter of a sphere or a long cylinder). One expects the following properties to be important in this process: the transport properties of the fluid (λ, η), the specific heat (C_p) and the density (ρ) of the fluid, the heat transfer coefficient (h), and the thermal convectional force ($f_{th} = -\rho\beta\theta g$, where $\theta = T_w - T_0$ is the temperature difference between the body and the fluids, and β the thermal expansion coefficient). The above convection process can be described by three independent dimensionless numbers:

$$\text{Nusselt number:} \quad Nu = \frac{hl}{\lambda} \quad \dots (7)$$

$$\text{Grashof number:} \quad Gr = \frac{l^3 \rho^2 g \beta \theta}{\eta^3} \quad \dots (8)$$

$$\text{Prandtl number:} \quad Pr = \frac{C_p \eta}{\lambda} \quad \dots (9)$$

A perfectly general equation for the free convection can now be written as

$$Nu = f(Gr, Pr) \quad \dots (10)$$

This is all the similarity analysis can provide. To determine the function $f(Gr, Pr)$ for the particular experimental situation, one must use an experimental approach or more elaborate theoretical methods. For laminar free convection (the inertial term in Stoke-Navier equation is negligible in comparison with the viscosity term), the definition of the Nusselt number in equation (10) is now written as:

$$Nu = f(GrPr) \quad \dots (11)$$

According to Hamzekhani S. et al (2014), natural convection from the outside surface of cylinders 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. A few pioneer experiments have been performed in which the influence of temperature gradient upon the rate of convective heat transfer from heated surfaces to fluid media have been investigated. The data are few, however, and due to the difficulty of conducting precise measurements in this field, are sometimes of doubtful validity.

The convective heat transfer data from circular cylinders have been summarized by Morgan (1975). According to his extensive survey, there is a wide dispersion in the published experimental data on natural convection from horizontal circular cylinders.

From the works of Collis and Williams (1954, 1966), Gosse (1956), Gebhard and Pera (1970) and Gebhard *et al.* (1970) using fine wires in air, it is clear that in hot wire measurement the end losses can be neglected if the aspect ratio l/D is larger than 10^5 . This condition is difficult to satisfy. Very few measurements have been made with $l/D > 10^4$. For smaller values of l/D , corrections for end heat losses have to be applied.

Morgan (1975), after a careful analysis of all published experimental data together with possible errors, proposed that

$$Nu = c(GrPr)^m \quad \dots (12)$$

where $c = 0.675$ and $m = 0.58$ for $GrPr$ from 10^{-10} to 10^{-2} . It is suggested that the proposed correlation has a maximum uncertainty of ± 5 . Among the other proposed correlations, that due to Kyte *et al.* (1953) is

$$Nu = \left\{ \ln \left[1 + \frac{7.09}{(GrPr)^{0.37}} \right] \right\}^{-1} \quad \dots (13)$$

Churchill and Chu (1975) published the following semi-empirical correlation equation

for heat transfer by natural convection from horizontal cylinders:

$$Nu = 0.36 + 0.518 \left\{ \frac{GrPr}{[1+(0.559/Pr)^{9/16}]^{16/9}} \right\}^{0.25} \dots (14)$$

Churchill and Chu state in their publication that this equation provides a good fit of representative data for all Pr and $10^{-6} \leq GrPr \leq 10^9$. The equation, however, did not match well with the experimental data for very low values of $GrPr \leq 10^{-6}$ which were the experimental data of Collis and Williams (1966). Another correlation, good for $10^{-11} \leq GrPr \leq 10^9$, was also developed by Churchill and Chu and is shown to be

$$Nu^{1/2} = 0.60 + 0.387 \left(\frac{GrPr}{[1+(0.559/Pr)^{9/16}]^{16/9}} \right)^{1/2} \dots (15)$$

Another correlation equation for horizontal cylinders is due to Raithby and Holland (1976).

$$Nu^{3.337} = \left\{ \frac{2}{\ln \left[\frac{1+\pi 2^{3/4}}{2.04A GrPr^{1/4}} \right]} \right\}^{3.337} + [0.72B (GrPr)^{1/3}]^{3.337} \dots (16)$$

$$\text{Where } A = \left(\frac{2}{3} \right) / [1 + (0.49/Pr)^{9/16}]^{4/9}$$

$B = 0.14 Pr^{0.084}$ or 0.15, whichever is smaller.

Conversely, the correlation equation for horizontal cylinders due to Kuehn and Goldstein (1980) is,

$$\frac{2}{Nu} = \ln \left[1 + \frac{2}{[0.518(GrPr)^{1/4} [1+(0.559/Pr)^{9/16}]^{16/9}]^{15}} \right] \dots (17)$$

This correlation as stated is valid for any Rayleigh and Prandtl number.

The average Nusselt number on the cylinder diameter calculated by Jaluria (1980),

obtained by an integral method valid for all Prandtl numbers in the range of Grashof number 10^5 and 10^{12} is

$$Nu = \left[\frac{Pr}{[1+(0.559/Pr)^{9/16}+10Pr]} \right]^{1/5} Ra^{1/4} \dots (18)$$

For laminar natural convection around the surface of a long cylinder with constant wall temperature according to authors Fand, Morris and Lum (1971), the equation is

$$Nu = 0.47Ra^{0.25}Pr^{0.047} \dots (19)$$

for range of Rayleigh number 3×10^2 to 2×10^7 and Prandtl number 0.7 to 3090. Furthermore, the empirical correlation where Nu and Gr are based on the characteristic length as proposed by Neetu et al (2014) from an inclined cylinder is

$$Nu^{1/2} = 0.54 + a \left[\frac{PrGr}{[1+(0.559/Pr)^{9/16}]^{16/9}} \right]^b \dots (20)$$

This correlation is of the form proposed by Churchill and Chu where $a = 0.390$ and $b = 0.1685$. The experimental range of the Prandtl number ranges from 0.68 – 0.72 and Grashof number varies between 1.4×10^4 to 1.2×10^{10} .

2.0 Inclined Cylinders

High viscosity is one of the most distinctive characteristics of glycerin. This quality is of value in a number of mechanical applications for glycerin such as a hydraulic fluid or a special lubricant, in laboratory studies of fluid flow phenomena and in viscometer calibrations, where aqueous solutions of glycerin are used as standards. At normal temperatures, glycerin remains a viscous liquid up to 100% concentration. Thus, it is available for use over a wide range of viscosities without crystallization difficulties. Likewise, at low temperatures, concentrated

glycerin suction tend to supercool as high-viscosity fluids. When glycerin super cools, its viscosity increases slowly at first, and then rapidly, until it becomes glassy at about -89°C . Viscosities of various concentrations of glycerin in water at various temperatures have been investigated, Cheng N. S, (2008).

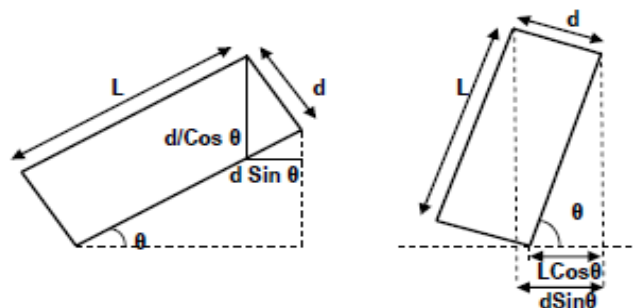
Natural convective heat transfer in cylindrical geometry has been widely studied for its application in heat loss from piping, heat exchangers, HVAC (Heating, Ventilation, and Air Conditioning) systems, etc. Natural convective heat transfer phenomena are two dimensional on vertical and horizontal cylinders but are three dimensional on inclined cylinders due to the circumferential and axial developments of the boundary layers making the flow as well as heat transfer behavior complex (Cameron and Patten, 1911). A number of correlations are available in literature for the estimation of natural convection heat transfer from vertical as well as horizontal cylinders, but little work has been reported on the effect of cylinder inclination on the mean heat transfer coefficient, (Neeta et al, 2014). Functional form of equation (11) can in particular, be written as

$$Nu = a(Gr^b Pr^c) \quad (21)$$

where Nusselt number and Grashof number are based on a characteristic length L_c . This characteristic length, L_c is defined as

$$L_c = \left[\frac{Ld}{(L/d)\cos\theta + (d/L)\sin\theta} \right]^{1/2} \quad (22)$$

As shown in the following figure, $d\sin\theta$ is the longitudinal projection of cylinder diameter on horizontal axis and $L\cos\theta$ is the longitudinal projection of cylinder length on horizontal axis.



3.0 Determination of the Free Nusselt Number

We shall use different correlations due to Churchill & Chu, Raithby & Holland, Kuehn & Goldstein, Faud et al, Neeta et al and Jaluria et al to determine the free Nusselt number. The Nusselt number is plotted against the natural log of the Raleigh number for each correlation.

The plots investigate the effect the orientation of the cylinder has on the Nusselt number. Three regimes of Raleigh numbers are treated. Further plots investigate the relationship between the Nusselt number and the orientation of the cylinder.

3.1 RESULTS AND DISCUSSION

We have evaluated free convective Nusselt number, Nu in glycerol as a function of cylinder orientations using correlations proposed by Churchill & Chu, Raithby & Holland, Kuehn & Goldstein, Fand et al, Jaluria et al and Neeta et al. Additionally, the

Nusselt number is plotted against the orientation of the cylinder for given Rayleigh numbers.

The variation of Nusselt number with cylinder orientation is investigated. The Nusselt number for each correlation is plotted against the log of Rayleigh number for the cylinder that is initially set at angle zero (horizontal), then at 10° , 20° , 30° , 40° , 50° , 60° , 70° , 80° and

90° (vertical) as shown in Fig1. There is a marked increase in the Nusselt number as the orientation reaches the angle 80° . This is to be expected as the coaxial force of gravity runs the entire characteristic length of the cylinder when in the vertical state. It is worth to note that the increase is initially quite small and rises to a remarkable level between 80° and 90° ; a position where the equilibrium of the cylinder is stable.

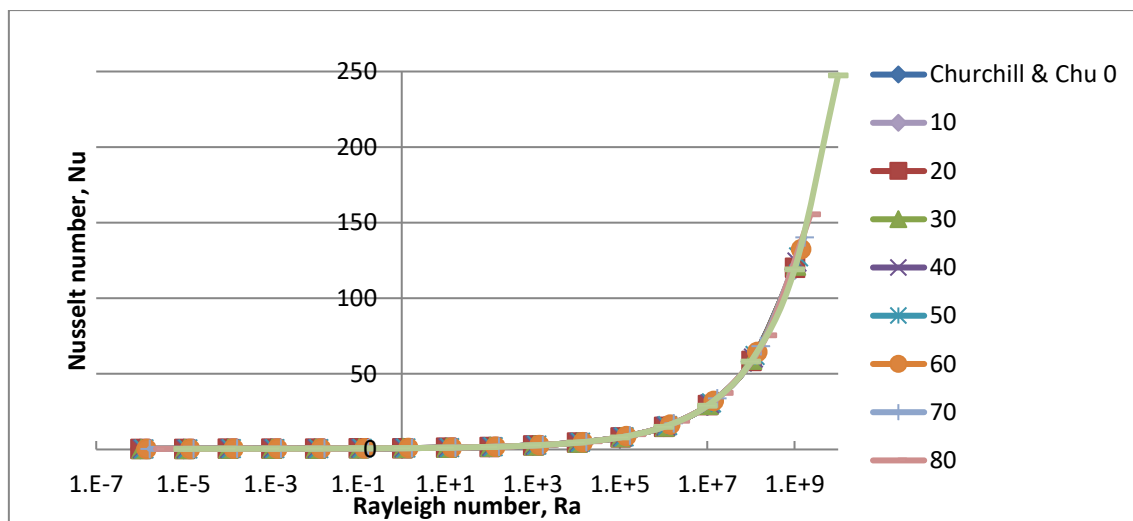


Figure 1 Nusselt number vs Rayleigh number with varying inclination using Churchill & Chu Correlation

Further, the Rayleigh number is set at three regimes of 10^{-6} , 10^0 and 10^9 and the Nusselt number is varied with the orientation of the cylinder from angle zero (horizontal), to 10° , 20° , 30° , 40° , 50° , 60° , 70° , 80° and 90° (vertical) as shown in Fig 2. The Nusselt number gradually increases with the tilt from angle zero to a

maximum at angle 90° , the vertical position. The increase from 80° to 90° is outstanding (Fig 2), especially at high Rayleigh numbers. Within this range, the Nusselt number obtained using the Raithby & Holland correlation is raised by about 100 units.

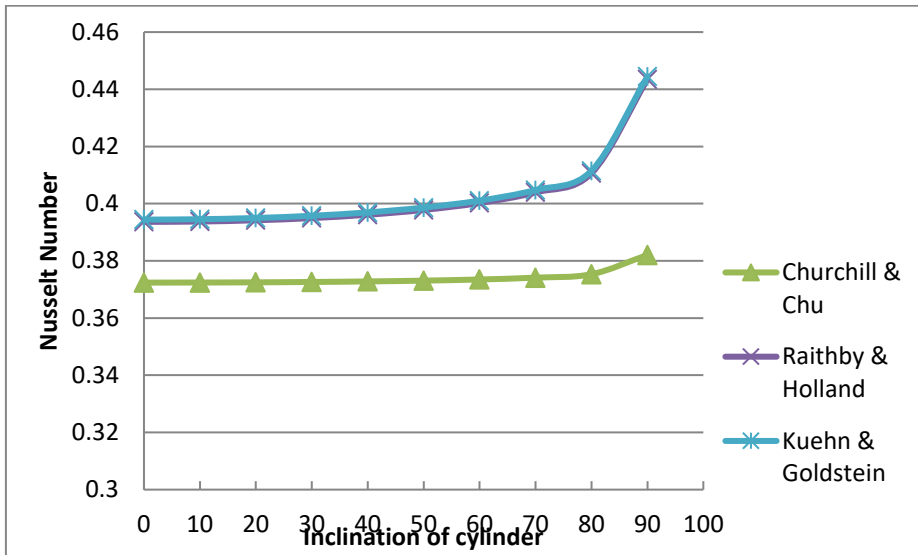


Fig 2a: Plot of Nusselt Number Vs Cylinder Orientation when Ra = 10⁻⁶

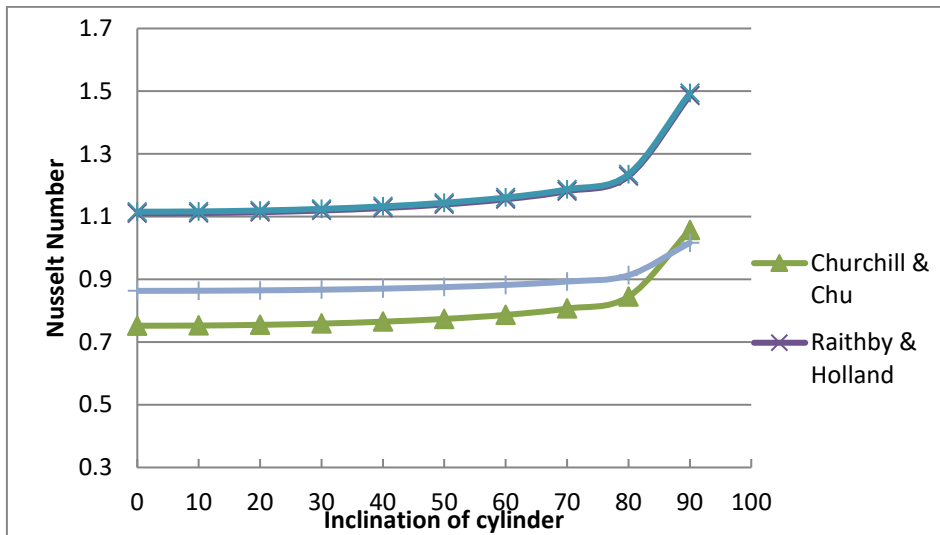


Fig 2b: Plot of Nusselt Number Vs Cylinder Orientation for Ra = 10⁰

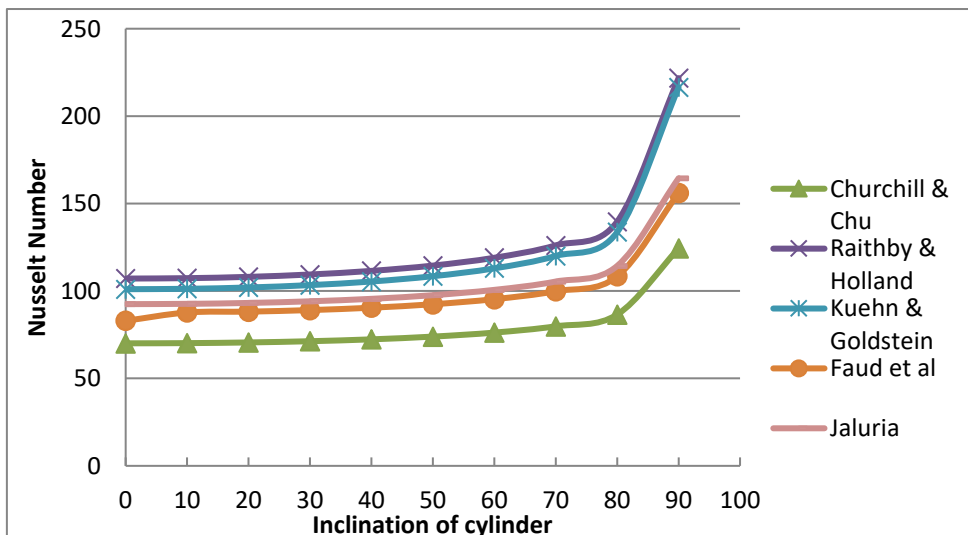


Fig 2c: Plot of Nusselt Number Vs Cylinder Orientation for Ra= 10⁹

3.2 Percentage increase in Nusselt number with cylinder orientation

The variation of the Nusselt number with orientation of the cylinder is shown in Table 1. When the cylinder is horizontal, that is when the angle of tilt is 0° , the Nusselt number for the correlation of Churchill & Chu, Raithby & Holland and Kuehn & Goldstein change basically from 0.37 to 0.44 as the tilt is raised to the vertical

position, 90° . This is the case when the Rayleigh number is small, that is, 10^6 . The increase in the heat flow still remains insignificant even at $Ra = 10^9$ but becomes remarkable at $Ra = 10^9$. At $Ra = 10^9$, the Nusselt number reaches as high as 163 for Neeta et al correlation. The enhanced increase is particularly clear between the orientations of 80° to 90° .

Table 1a: Nusselt Number obtained when Rayleigh Number is 10^6

Churchill & Chu	Raithby & Holland	Kuehn & Goldstein	Cylinder inclination, θ
0.3724	0.39362	0.39443	0
0.37242	0.39375	0.39456	10
0.37249	0.39419	0.395	20
0.37261	0.39496	0.39577	30
0.3728	0.39612	0.39694	40
0.37308	0.39781	0.39863	50
0.37349	0.40024	0.40107	60
0.37413	0.40395	0.4048	70
0.37532	0.41063	0.41151	80
0.38204	0.44344	0.44446	90

Table 1b: Nusselt Number obtained when Rayleigh Number is 10^9

Churchill & Chu	Raithby & Holland	Kuehn & Goldstein	Faud et al	Jaluria	Neeta et al	Cylinder inclination, θ
0.75201	1.11041	1.11571	0.46652	0.52013	0.74513	0
0.75267	1.11128	1.11658	0.46731	0.52101	0.74577	10
0.75489	1.11419	1.11951	0.46995	0.52395	0.7479	20
0.75883	1.11935	1.12472	0.47465	0.52919	0.75167	30
0.76487	1.12723	1.13265	0.48182	0.53719	0.75746	40
0.77366	1.13867	1.14418	0.49229	0.54886	0.76587	50
0.78657	1.15536	1.16099	0.50766	0.56599	0.77819	60
0.80675	1.18123	1.18705	0.53167	0.59227	0.79741	70
0.84456	1.22901	1.23518	0.57666	0.64292	0.83328	80
1.0571	1.48596	1.49386	0.82961	0.92494	1.03311	90

Table 1c: Nusselt Number obtained when Rayleigh Number is 10^9

Churchill & Chu	Raithby& Holland	Kuehn & Goldsteiin	Faud et al	Jaluria	Neeta et al	Cylinder inclination, θ
70.07026	107.11293	101.03627	82.96092	92.49377	124.471	0
70.16641	107.33882	101.26207	83.10152	92.65052	124.742	10
70.58249	108.09313	102.01619	83.57052	93.17342	125.646	20
71.28394	109.439	103.36201	84.4053	94.10412	127.259	30
72.35649	111.50486	105.42856	85.68172	95.52722	129.735	40
73.92058	114.53457	108.46084	87.54311	97.60249	133.366	50
76.21657	119.01828	112.95152	90.27554	100.64889	138.741	60
79.80542	126.11142	120.06266	94.54655	105.41068	147.247	70
86.52746	139.66637	133.67232	102.54634	114.32971	163.506	80
124.32432	221.75906	216.44677	147.52769	164.47977	262.086	90

Likewise, the percentage increase in the Nusselt number is evaluated as the tilt to the horizontal is changed from 0^0 to 90^0 . This remarkable increase is even more manifested in table 2 where the percentage Nusselt number is

evaluated with respect to orientation. The Kuehn and Goldstein correlation records the highest value of 114% increase in the Nusselt number at an inclination of 90^0 when the Rayleigh number is 10^9 .

Table 2a: Percentage increase in Nusselt Number ($Ra = 10^6$)

Churchill & Chu	Raithby& Holland	Kuehn & Goldstein	Cylinder inclination. θ
0	0	0	0
0.005371	0.03303	0.03296	10
0.02417	0.14481	0.14451	20
0.05639	0.34043	0.33973	30
0.10741	0.63513	0.63636	40
0.1826	1.06448	1.06483	50
0.29269	1.68183	1.68344	60
0.46455	2.62244	2.62911	70
0.7841	4.32143	4.3303	80
2.58861	12.65688	12.68413	90

Table 2b: Percentage increase in Nusselt Number (Ra = 10⁰)

Churchill & Chu	Raithby& Holland	Kuehn & Goldstein	Faud et al	Jaluria	Neeta et al	Cylinder inclination. θ
0	0	0	0	0	0	0
0.08776	0.07835	0.07798	0.169338935	0.169188472	0.085744905	10
0.38297	0.34041	0.34059	0.735231073	0.734431777	0.371052893	20
0.9069	0.80511	0.80756	1.74269056	1.741872224	0.877718358	30
1.71008	1.51476	1.51832	3.279602161	3.279949243	1.654123901	40
2.87895	2.54501	2.55174	5.523878933	5.523619095	2.783202077	50
4.59568	4.04805	4.0584	8.81848581	8.817026513	4.436414005	60
7.27969	6.37782	6.39413	13.96510332	13.86960952	7.016449581	70
12.30702	10.68074	10.70798	23.6088485	23.60755965	11.82950406	80
40.56994	33.82084	33.89322	77.82946069	77.82861977	38.64795821	90

Table 2c: Percentage increase in Nusselt Number (Ra = 10⁹)

Churchill & Chu	Raithby& Holland	Kuehn & Goldstein	Faud et al	Jaluria	Neeta et al	Cylinder inclination. θ
0	0	0	0	0	0	0
0.137219	0.21089	0.22348	0.1695	0.16947	0.21739	10
0.731023	0.915109	0.96987	0.7348	0.73481	0.94372	20
1.73209	2.171605	2.30189	1.741	1.74104	2.23941	30
3.262768	4.10028	4.34724	3.2796	3.27963	4.22854	40
5.494942	6.928799	7.34842	5.5233	5.52331	7.146	50
8.771639	11.11476	11.793	8.8169	8.81694	11.4645	60
13.89343	17.73688	18.8312	13.965	13.9652	18.2976	70
23.48671	30.3917	32.3013	23.608	23.608	31.3603	80
77.42808	107.033	114.227	77.828	77.8279	110.559	90

4.0 CONCLUSION

Using the established correlations of Churchill & Chu, Raithby& Holland, Kuehn & Goldstein, Fand et al, Jaluria and Neeta et al, the effect of orientation on the free convective heat transfer in glycerol is studied for the range of Rayleigh number, $10^{-6} \leq Ra \leq 10^9$ and for all Prandtl numbers. The Nusselt number plotted against the log of Rayleigh number for the different correlations are hyperbolic curves as expected for convection.

Heat transfer for free convection from an inclined cylinder has been investigated at different Raleigh

numbers. It is evident that at any tilt of the cylinder, the average Nusselt number increases with increasing Raleigh number. For any Rayleigh number, the Nusselt number increases with increasing orientation of the cylinder. The orientation of a cylinder has its characteristic Nusselt number when the Rayleigh number is fixed and unified correlation may be formed which can be applied to predict the natural convection heat transfer for all horizontal, vertical and inclined cylinders.

The sudden hike in heat transfer for the range of angle of inclination between 80° and 90° is somewhat linear. This linear variation of the Nusselt number with the orientation of the cylinder may be instructive and can be graduated for appropriate assessment of heat transfer.

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