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EFFECT OF FLOWRATE VARIATION ON MODES OF HEAT LOSSES FROM A SINGLE PIPE: A COMPARATIVE ANALYSIS

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ABSTRACT

An experimental investigation into the effect of varying water flowrate on heat losses from a single galvanized pipe into the surrounding environment was undertaken. A bench-scale laboratory apparatus named Liquid Measurement and Heat Transfer Trainer was used for the investigation. Hot water heated up by three thermostat-heater elements, housed inside a re-inforced PVC tank, was circulated at various flowrates, by a current-driven centrifugal pump, through a galvanized pipe of 33.40mm O.D., 26.64mm I.D. and total length 4500mm. The exit temperature from the tank, entry temperature into the tank, and the room temperature were recorded at various flowrates when steady temperatures were attained. These temperatures were captured with electronic, mercury-in-glass and alcohol-in-glass thermometers respectively. Subsequently, the quantities of heat losses from single pipe by modes of conduction, convection and radiation were evaluated. Comparatively, the results obtained showed that heat losses to the room environment from a cylindrical pipe carrying circulating hot water, is highest by conduction mode, and least by radiation mechanism.

Keywords: experimental investigation, flowrate variation, conduction mode, convection mode, radiation mode, comparative analysis and heat- losses evaluation.

INTRODUCTION

Heat exchange is a common phenomenon and operation in many homes and the process industries. In many residential buildings, water-bearing pipes from the mains supply, or from overhead tank supply, which are exposed to the indoor, or outdoor environments usually exchange heat with their immediate surrounding environments. This is essentially what this apparatus named, Heat Transfer Trainer, is designed to investigate.

The Heat Transfer Trainer, locally designed and fabricated for the purpose of enhancing the inadequacy of teaching and research equipment in Nigerian universities, has the following technical data.

Test-pipe length (silver painted) : 4.5m
Test-pipe diameter (silver painted): 33.40mm O.D.
: 26.64mm I.D.
Test-pipe thickness: 3.38mm

In the Heat Transfer Trainer, hot water from sump tank is circulated by the current-driven centrifugal pump through the 4.5m long test-pipe. The sump tank is electrically heated and the temperature of the water in the sump tank is maintained by the thermostat. The trainer is designed so that the circulation of hot water may be manually adjusted by the ball valve fitted into the test-pipe at the sump tank entrance. To ensure temperature measurements in between the 4.5m test-pipe length, two thermowells located at the outlet (exit) of the test-pipe from the sump tank, the other at the inlet (entrance) of the test-pipe into the sump tank permit the accomplishment of this objective.

The study of the EFFECT OF FLOWRATE VARIATION ON HEAT LOSSES MODES was achieved by the recording of six pairs of temperature observations from the Heat Transfer Trainer, after each and every flowrate adjustment. The temperature of the surrounding environment was also recorded after every adjustment of flowrate.

The application of conductive, convective and radiative heat transfer equations and methods for the evaluation of heat loss from single bare pipe of known length was the goal of this study. Also, a comparative analysis of the modes of heat loss was another goal of this investigation.

Conduction Heat Loss from a Hot Pipe

The transfer of heat through a fixed material is accomplished by the mechanism known as conduction, and the rate of heat flow by conduction is proportional to the area available for the heat transfer and the temperature gradient in the direction of the heat-flow path, Peters and Timmerhaus, (1981)[1].

For a cylindrical pipe in which the area of heat transfer is given as $A_r = 2\pi rL$, Holman (1976)[2], Incropera and DeWitt (1985)[3], Nnolim (1995)[4], Rajput (1999)[5] and Coulson and Richardson (1999)[6] gave the heat loss as:

$$Q_{cond} = \frac{2\pi kL\,(T_i - T_o)}{\ln\left(\frac{r_o}{r_i}\right)} \qquad \ldots(1)$$

where all the symbols are defined in the Notation Section.

Convection Heat Loss from a Hot Pipe

According to Peters and Timmerhaus (1981)[1] transfer of heat by physical mixing of the hot and cold portions of a liquid is known as heat transfer by convection; the mixing can occur as a result of density differences alone, as in natural convection, or as a result of mechanically induced agitation, as in forced convection.

The total heat transfer by convection can be evaluated by the equation written by Holman (1976)[2]:

$$Q_{conv} = hA\,(T_w - T_b) \qquad \ldots(2)$$

where the symbols are defined in the Notation Section.

Because both T_w and T_b can be very along the length of the pipe (L), a suitable average process must be adopted for use with eqn(2).

Coulson and Richardson, (1999)[6] states that the physical properties except the viscosity are taken at the mean bulk temperature of the fluid in accordance with the expression below:

$$T_{bm} = \frac{T_{bO} + T_{bI}}{2} \qquad \ldots(3)$$

These procedures left the heat transfer test-pipe open for hot water circulation. By switching on the centrifugal pump, hot water circulated from the sump tank into the heat transfer test-pipe (incorporating the thermowell T_{b1}, the gate valve, the thermowell T_{b2}, the ball valve) and back into the sump. Two minutes were allowed for hot water circulation to settle down and remain steady, after which the flow rates (q) were measured and recorded; also temperatures were measured and recorded using electronic, mercury-in-glass and alcohol-in-glass thermometers, respectively. By adjusting the ball valve to different degrees of opening, namely 75^0, 60; 45^0, 30^0 and 15^0; the effect of varying flowrates on heat losses by conduction, convection and radiation were studied. The categories of readings obtained are as follows.

Table 1: Electronic thermometer recordings

Degree of valve opening(P^0)	q (m^3/sec)	T_{b1} (^{0}c)	T_{b2} (^{0}c)	T_{w1} (^{0}c)	T_{w2} (^{0})	T_∞ (^{0}c)
90	1.3×10^{-4}	75	73.3	52.2	43.0	33.0
75	1.05×10^{-4}	74.8	73.0	50.4	41.2	33.2
60	1.01×10^{-4}	75.4	73.8	52.3	43.5	33.2
45	8.9×10^{-5}	73.1	70.7	49.7	44.1	33.0
30	7.0×10^{-5}	75.1	72.1	51.8	42.4	32.9
15	3.5×10^{-5}	74.8	73.6	54.1	41.6	32.1

Table 2: Alcohol-in-glass thermometer recordings.

Degree of valve opening(P^0)	q (m^3/sec)	T_{b1} (^{0}c)	T_{b2} (^{0}c)	T_{w1} (^{0}c)	T_{w2} (^{0})	T_∞ (^{0}c)
90	1.30×10^{-4}	72.0	68.0	50.0	41.0	33.0
75	1.05×10^{-4}	70.0	66.5	48.0	40.6	33.2
60	1.01×10^{-4}	71.0	67.8	48.3	40.6	33.2
45	8.9×10^{-5}	72.5	68.0	48.8	40.9	33.0
30	7.0×10^{-5}	69.7	66.0	47.0	39.0	32.9
15	3.5×10^{-5}	70.0	67.0	46.0	39.0	32.1

Table 3: Mercury-in-glass thermometer recordings.

Degree of valve opening (p^0)	q (m^3/sec)	T_{b1} (^{0}c)	T_{b2} (^{0}c)	T_{w1} (^{0}c)	T_{w2} (^{0})	T_∞ (^{0}c)
90	1.30×10^{-4}	74.8	73.0	51.8	43.0	33.0
75	1.05×10^{-4}	74.7	73.0	50.1	41.1	33.2
60	1.01×10^{-4}	75.0	73.2	51.7	43.0	33.2
45	8.9×10^{-5}	74.4	71.3	50.3	43.9	33.0
30	7.0×10^{-5}	74.9	71.9	50.0	42.0	32.9
15	3.5×10^{-5}	74.8	72.1	51.1	42.4	32.1

Note

T_{b1}: outlet temperature of water leaving sump
T_{b2}: inlet temperature of water entering sump
T_{w1}: wall temperature of the sump outlet pipe
T_{w2}: wall temperature of the sump inlet pipe
T_∞: room temperature

Methods of Data Treatment and Analyses

The data from the experiments were subjected to heat losses evaluations and analyses by applying the relevant equations reviewed earlier for conduction, convection and radiation. In this regard, the following evaluations and analyses were undertaken from the experimental data.

- The mean bulk temperatures (T_{bm}) at various degrees of valve openings were determined using eqn(3).
- The mean pipe-wall temperatures (T_{wm}) at various degrees of valve openings were calculated using eqn(4).
- The heat loss by conduction (Q_{cond}) were evaluated for various degrees of valve openings by applying eqn(1).
- The heat loss by convection (Q_{conv}) were determined for various degrees of valve openings by using eqns(5) and (2).
- The heat loss by radiation (Q_{rad}) were computed for various degrees of valve openings by employing eqn(6).
- The plots of heat loss by conduction (Q_{cond}), convection (Q_{conv}), and radiation (Q_{rad}) against flowrate(q) were produced.

RESULTS AND DISCUSSION

The result of evaluations of heat losses by modes of conduction (Q_{cond}), convection (Q_{conv}) and radiation (Q_{rad}) at various flowrates are presented for discussion in the Table and Figures below.

Table 4: Heat losses from single pipe

Degree of valve opening (P^0)	q (m^3/s)	Q_{cond} (W)	Q_{conv} (W)	Q_{rad} (W)
15	3.5×10^{-5}	177,600.00	10,246.77	36.57
30	7.0×10^{-5}	168,821.30	9,209.13	32.86
45	8.9×10^{-5}	168,821.30	9,014.57	32.15
60	1.01×10^{-4}	180,301.10	9,533.39	34.20
75	1.05×10^{-4}	189,755.10	8,171.48	29.02
90	1.30×10^{-4}	179,625.81	9,468.54	33.89

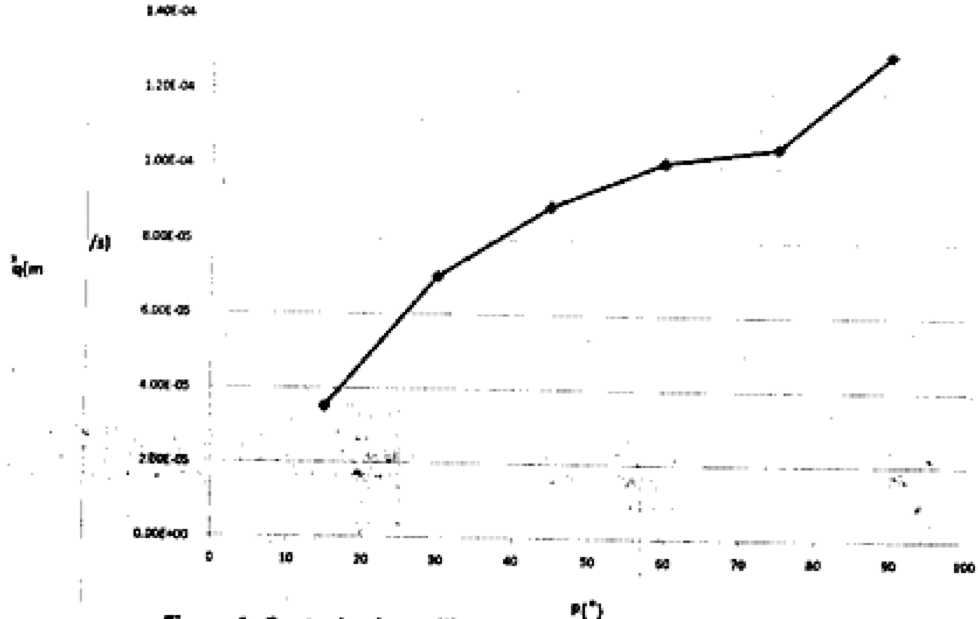

Figure 1: Control valve calibration plot (discharge, m /s versus degree of valve opening, P)°

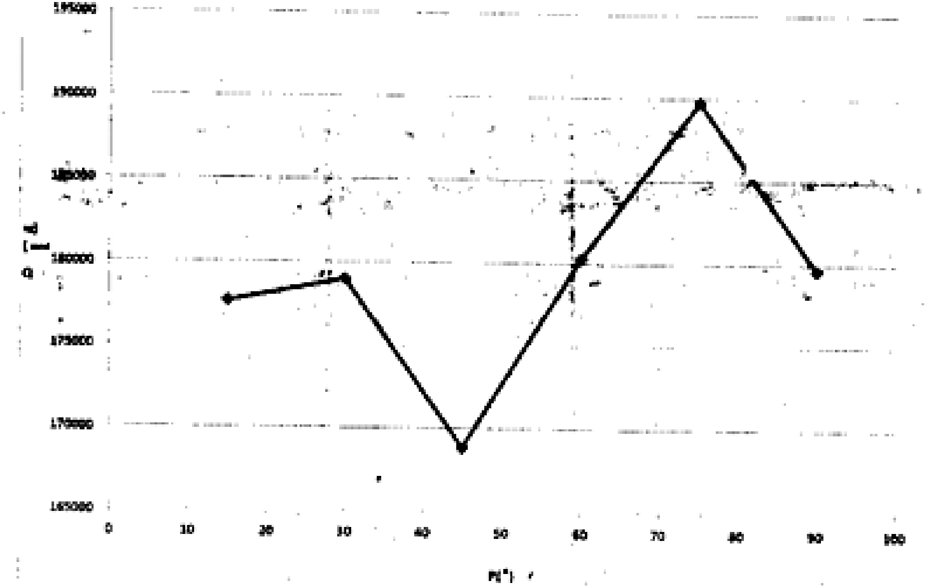

Figure 2: Plot of heat loss by conduction Q $_{cond}$ (W) versus degree of valve opening P °

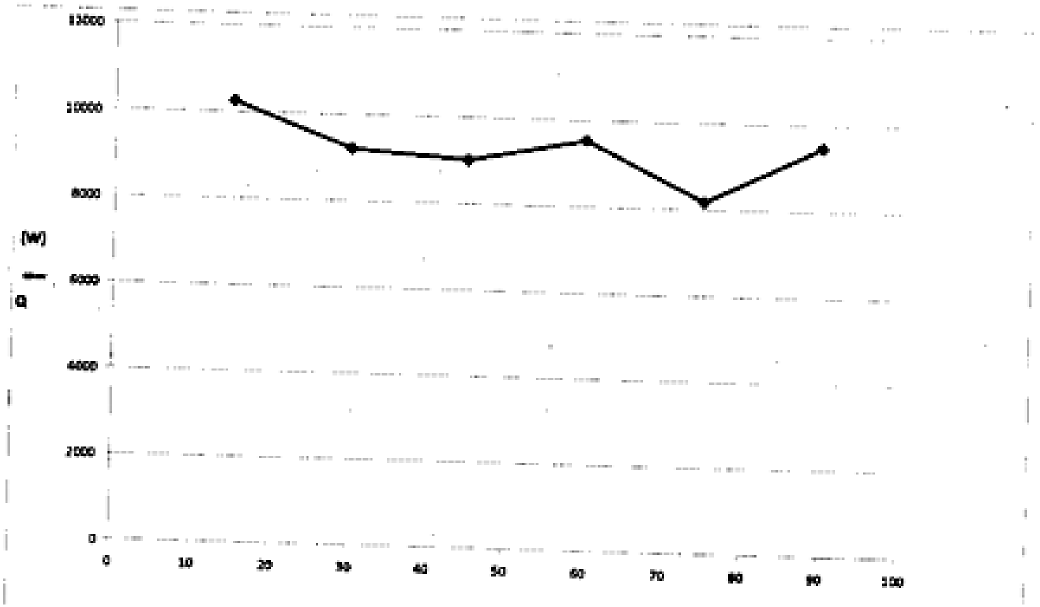

Figure 3: Plot of heat loss by convection Q_{conv} (W) versus degree of valve opening P(°)

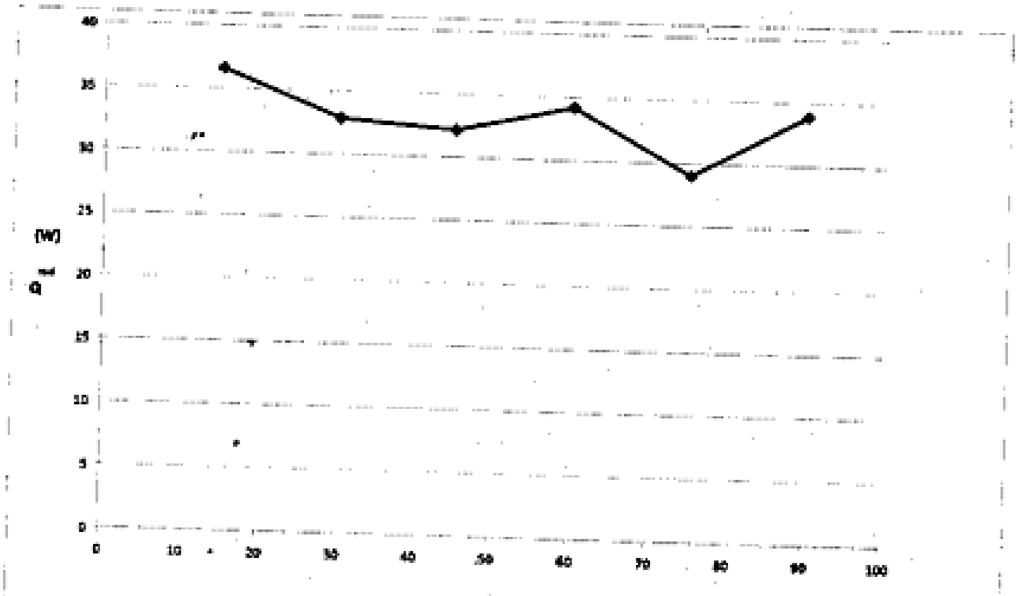

Figure 4: Plot of heat loss by radiation Q_{rad} (W) versus degree of valve opening P(°)

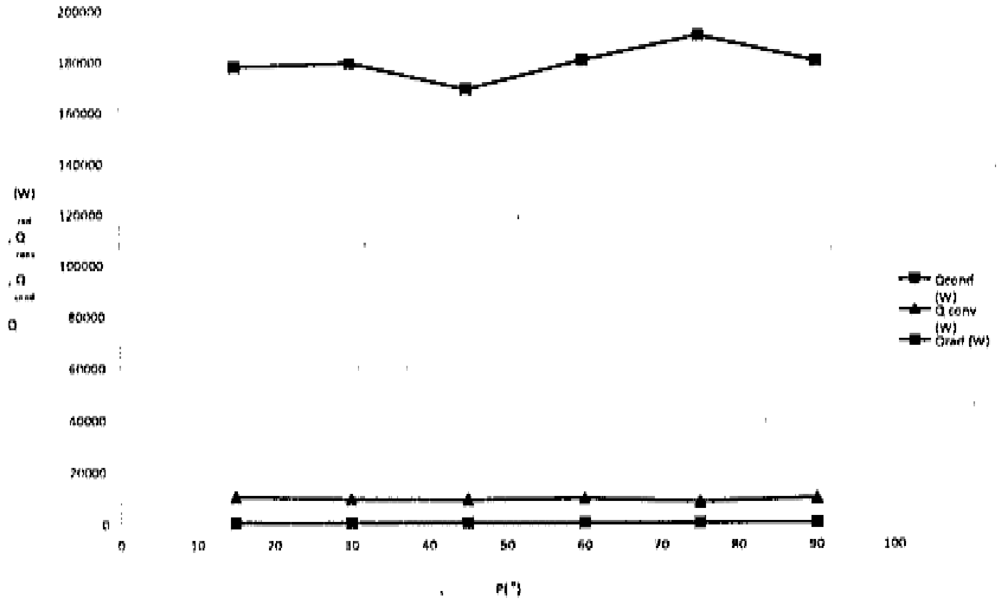

Figure 5: Comparative plots of Q_{cond}, Q_{conv} & Q_{rad} (W) against degree of valve opening P(°)

The calibration plot (Figure 1) approximates to an uprising straight line. This is suggestive that the flowrate, q(m^3/s) is directly proportional to the degree of valve opening (P^0). Figure 2 is the graph of Q_{cond} versus the degree of valve opening (hot water flowrate). In terms of magnitude, with an average value of 179,176W (179.18kW), Figure 2 depicts the highest quantity of heat loss from the single pipe. This implies that most of the heat loss from the single pipe is by conduction mechanism, and the conduction mode of heat loss from single pipe overwhelms other heat-loss modes, namely convection and radiation. In terms of graphic trend, Figure 2 exhibits alternate rising and falling trend of Q_{cond} over varying hot water flowrates. This trend (Figure 2) suggests that on the average there exists a steady linear relationship between heat loss by conduction (Q_{cond}) and hot water flowrate.

Figure 3 is the graph of Q_{conv} against the degree of valve opening (hot water flowrate). Considering the magnitude of heat loss, Figure 3 bearing an average value of 9,440.65W (9.44kW) for Q_{conv} reflects some significant quantity of heat loss, but not upto the staggering amount of heat loss (179,176W) depicted by Q_{cond} (Figure 2). This implies that in terms of quantity of heat loss from the hot water bearing pipe, heat loss by convection (Q_{conv}) ranks second to heat loss by conduction (Q_{cond}). Subsequently, the trend of Figure 3 depicts alternate rising and falling pattern of Q_{conv} over increasing hot water flowrate. This pattern of Figure 3 suggests that on the average heat loss by convection (Q_{conv}) is fairly steady for increasing hot water flowrate.

Also Figure 4 is the graph of heat loss by radiation (Q_{rad}) versus degree of valve opening (hot water flowrate). The quantity of heat loss by radiation (Q_{rad}) averages 33.12W, and this is the least in magnitude when ranked with the quantity of heat loss by conduction (179,176W) and convection (9,440.65W). In simple term, this implies that the least of the heat loss from the hot-water bearing pipe is by radiation mechanism. This may be so, because the pipe surface is grey in colour. Perhaps higher quantity of heat loss may have been accomplished by radiation mode (Q_{rad}) if the pipe surface is painted black. Also, the graphic trend of Figure 4 portrays alternate growing and declining pattern of Q_{rad} over different hot water flowrates. Subsequently, this trend (Figure 4) suggests that the average heat loss by radiation (Q_{rad}) is fairly constant for varying hot water flowrates. The fluctuating patterns of Q_{cond}, Q_{conv} and Q_{rad} over varying flowrates, is a consequence of temperature fluctuations at different flowrates. However, these temperature fluctuations may likely be as a result of:

(a) Unsteady power supply from the mains

(b) Defects in the thermostats which may affect the heating elements' performances.

(c) The material of construction of the pump impeller, which in this case is plastic (poly vinyl chloride) impeller. May be a brass-cast impeller would improve and change the result from fluctuating patterns into steady trends.

Figure 5 shows the comparative plots of Q_{cond}, Q_{conv} and Q_{rad} against the degree of valve opening (hot water flowrate). Also Figure 5 characterized and differentiated Q_{cond}, Q_{conv} and Q_{rad} according to their respective magnitudes. From Figure 5, Q_{cond} is the largest in magnitude, and Q_{rad} is the least in magnitude, while Q_{conv} lies in between Q_{cond} and Q_{rad} in magnitude. To this end, it will be correct to state comparatively that heat loss from the single pipe is overwhelmingly by conduction mode, while the loss by radiative mechanism showed the least heat loss quantity (see Figure 5).

CONCLUSION AND RECOMMENDATION

One of the novelties derived from this study is the creativity and innovation involving hands-on application and employment of analytical approach and tools to determining heat losses from a cylindrical conduit by modes of conduction, convection and radiation.

Interestingly, the study has successfully demonstrated that the Nigerian-made Heat Transfer Trainer has a promise for:

(1) Ensuring and enhancing the practical appreciation of heat transfer fundamentals for users, and thereby minimizing hypothetical knowledge of heat transfer.

(2) Inculcating hands-on experience on users and thereby making learning active, in contrast with passive learning.

In a nutshell the result from the study showed that heat losses to the environment from a single pipe bearing circulating hot water is overwhelmingly by conduction mode and least by radiation mechanism.

It is therefore expected that the results from the study will inspire the widening of the scope of practical learning of heat transfer from cylindrical conduit to the outside environment

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NOTATIONS

Q	Amount of heat transferred	W
k	Thermal conductivity	W/m^{0}C
L	Length of conduction path in heat flow direction	m
r_0	Outside radius of cylinder or radial system	m
r_i	Inside radius of cylinder or radial system	m
$(T_i - T_0)$	Differential temperature in the radial direction	^{0}C
$(T_{b2} - T_{b1})$	Bulk – temperature difference in axial direction	^{0}C
T_w	Wall temperature at a particular location	^{0}C
T_∞	Temperature of environment (surroundings)	^{0}C
T_b	Bulk temperature at a particular location	^{0}C
h	Heat transfer coefficient	W/m^2. ^{0}C
A	Total surface area for heat transfer (2πrL or πDL)	m^2
ε	Emissivity of hot surface	W/m^2
q	Volume flowrate	m^3/s
Q_{cond}	Heat loss by conduction from hot pipe	W
Q_{conv}	Heat loss by convectin from hot pipe	W
Q_{rad}	Heat loss by radiation from hote pipe	W
T_1	Temperature of surface 1	^{0}C
T_2	Temperature of surface 2	^{0}C
t_b	Average bulk temperature of water	^{0}F
V'	Velocity of water	ft/s
D'	'' Diameter	inches
h_i	Heat transfer coefficient for water at ordinary temperatures and pressures	Btu/(h)(ft^2)(^{0}F)