Laminar/viscous flow heat transfer experiment

Reference: PA Hilton Ltd. Experimental, Operating & Maintenance Manual: Laminar/Viscous Flow Heat Transfer Unit H970, H970M/E/3, 1988.

Objectives

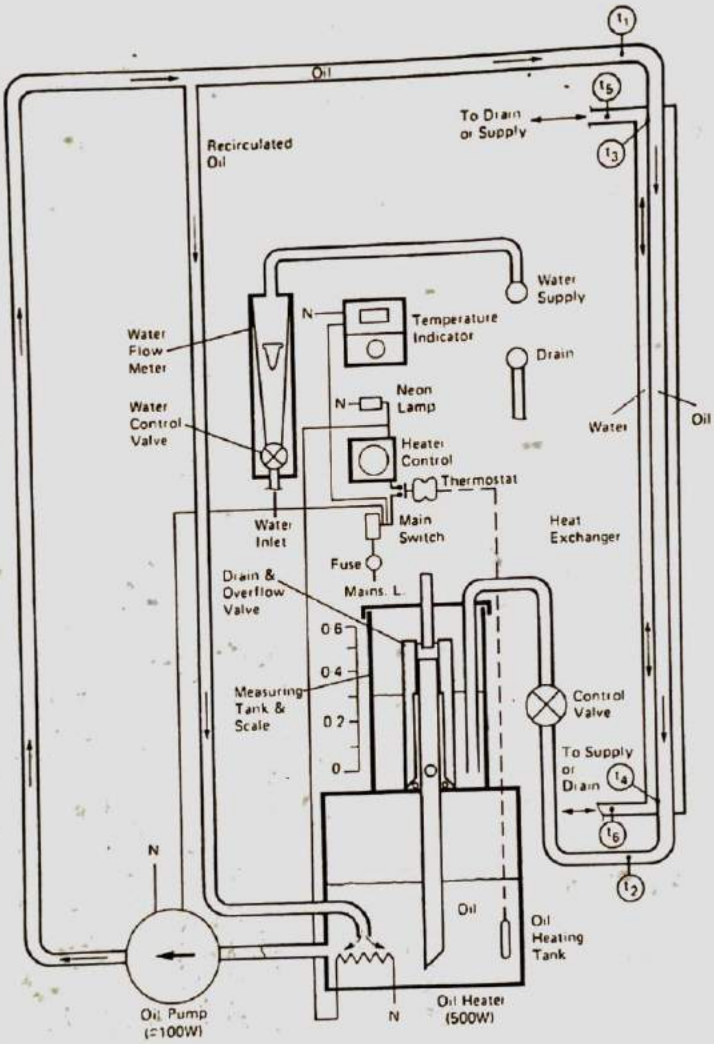
This experiment assists you to achieve the following objectives:

- Understand the working principles of a counter-current laminar flow heat exchanger.
- Conduct an energy-balance analysis for a simple heat exchanger.
- Determination of surface heat transfer coefficients on both the oil and water sides, and of the overall heat transfer coefficient.
- Understand the relationship between Nusselt and Graetz numbers for laminar flow in a circular pipe.
- Develop a direct tangible feel for the typical control time constant for heat transfer process control.

Hardware specifications

Heat exchanger:

Core tube	Material – Copper		
	External diameter, d_o	=	12.7mm
	Internal diameter, d_i	=	11.3mm
	Effective length, L	=	910mm
	External heat transfer area, A_o	=	$0.0365 m^2$
	Internal heat transfer area, A_i	=	$0.0323 m^2$
	Mean heat transfer area, A_m	=	$0.0342 m^2$
	Flow cross sectional area, S_i	=	$96.7\times10^{-6} m^2$
Outer tube	Material – Copper		
	External diameter	=	15.9mm
	Internal diameter	=	14.4mm
	Annulus flow cross sectional area	=	$36.2\times10^{-6} m^2$



Laminar/ Viscous Flow Heat Transfer Unit H970

P.A. Hilton Ltd. Experimental operating & maintenance manual: Laminar/viscous flow heat transfer unit H970, H970M/E/3, 1988.

Experimental procedures

(i) Ensure that the unit has been correctly filled with oil and prepared for use.

(ii) Fully open the oil flow control valve and raise the drain valve in the measuring tank.

(iii) Switch on the power supply and adjust the heater control to its maximum.

(iv) When the oil temperature, t_1, reaches about 70°C, turn on the cooling water and adjust the water flow rate to about 15 g/s.

(v) Adjust the heater input to give a steady oil temperature of about 77°C.

(vi) When conditions have stabilized make the observations set out below.

(vii) Partially close the oil control valve and while maintaining the water flow rate, adjust the heater to stabilize the oil temperature. It is important that the adjustment to the heater must be small each time. After every adjustment, allow 20 seconds or slight more for the adjustment to take effect in the system, before making another adjustment.[1]

(viii) When the system stabilizes, repeat the observation.

Measured Results

	1	2	3
Temperature of oil entering, t_1 (°C)	68.6	80.3	86.6
Temperature of oil leaving, t_2 (°C)	66.5	78.1	83.5
Quantity of oil collected, V (Litre)	0.5	0.5	0.5
Time to collect oil, T (s)	10.40	9.84	10.42
Temperature of tube metal at upper end, t_3 (°C)	30.0	31.7	30.7
Temperature of tube metal at lower end, t_4 (°C)	22.8	23.2	23.2
Water inlet temperature, t_6 (°C)	22.4	22.9	22.8
Water outlet temperature, t_5 (°C)	26.0	26.7	26.2
Water flow rate, $\dot{m}_w$ (g/s)	14.5	17.0	20.0

[1] This is a very important point that will help you develop a direct feel for the typical time constant for thermal process control. If your frequency of adjustment is too high, you will see that the system fluctuates wildly, and hardly tends to steady state. If your frequency of adjustment is too slow, on the other hand, the time taken for the experiment will take far longer. 20 seconds or so is a rough estimate of the time taken for the oil to make a complete loop, over which your prior manual adjustment will make a complete impact on the system behavior.

Derived Results

	1	2	3
Mean oil temperature, $(t_1+t_2)/2$ (°C)			
Oil c_p at mean temperature kJ/kg·°C			
Oil ρ at mean temperature kg/L			
Mean water temperature, $(t_5+t_6)/2$ (°C)			
Water c_p at mean temperature kJ/kg·°C			
Log mean temperature difference between oil and tube, $\theta_{lm,o\text{-}t}$ $=\dfrac{(t_1-t_3)-(t_2-t_4)}{\ln[(t_1-t_3)/(t_2-t_4)]}$ (°C)			
Log mean temperature difference between tube and water, $\theta_{lm,t\text{-}w}$ $=\dfrac{(t_3-t_5)-(t_4-t_6)}{\ln[(t_3-t_5)/(t_4-t_6)]}$ (°C)			
Log mean temperature difference between oil and water, $\theta_{lm,o\text{-}w}$ $=\dfrac{(t_1-t_5)-(t_2-t_6)}{\ln[(t_1-t_5)/(t_2-t_6)]}$ (°C)			
Oil mass flow rate, $\dot{m}_{oil}$ (kg/s)			
Rate of heat transfer from oil, $\dot{Q}_{oil}$ (W)			
Rate of heat transfer to water, $\dot{Q}_{water}$ (W)			
Energy balance, $\dot{Q}_{oil}-\dot{Q}_{water}$ (W)			
Surface heat transfer coefficient (oil to tube) $\overline{h}_{o\text{-}t}$ = $\dot{Q}_{oil}/A_i\theta_{lm,o\text{-}t}$ (W/m²·K)			

Surface heat transfer coefficient (tube to water) $\bar{h}_{t-w} = \dot{Q}_{oil}/A_o\theta_{lm,t-w}$ (W/m²·K)			
Overall heat transfer coefficient (oil to water) $U = \dot{Q}_{oil}/A_m\theta_{lm,o-w}$ (W/m²·K)[2]			
Mean velocity of oil, $u_{oil} = V/T/S_i$			
Oil kinematic viscosity at mean temperature, ν (10^{-6} m^2s^{-1})			
Oil thermal conductivity at mean temperature, k (W/m·K)			
Oil Nusselt number, $\bar{h}_{o-t}d_i/k$			
Oil Reynolds number[3], $u_{oil}d_i/\nu$			
Oil Graetz number[4], $\frac{4}{\pi}\frac{\dot{m}_{oil}c_p}{kL}$			

Data Analysis

(1) Discuss the energy balance, $\dot{Q}_{oil} - \dot{Q}_{water}$, vis-à-vis the experimental condition. Note that the measurement error for each of the thermocouple reading is about ±1.0°C.

(2) Plot the oil-to-tube and oil-to-water heat transfer coefficients with respect to the mean oil velocity. Explain the observed relationship between the heat transfer coefficients and the mean oil velocity.

(3) Plot the oil Nusselt number with respect to the oil Graetz number. Discuss why is the Nusselt number changing with the Graetz number.

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[2] $U = \dfrac{1}{\dfrac{A_m}{A_i}\dfrac{1}{h_{o-t}} + \dfrac{A_m}{A_o}\dfrac{1}{h_{t-w}}}$

[3] A laminar flow is characterized by $Re_D < 2300$.

[4] $\text{Graetz number}_L = \dfrac{Re\,Pr}{L/d_i} = \dfrac{4}{\pi}\dfrac{\dot{m}_{oil}c_p}{kL}$

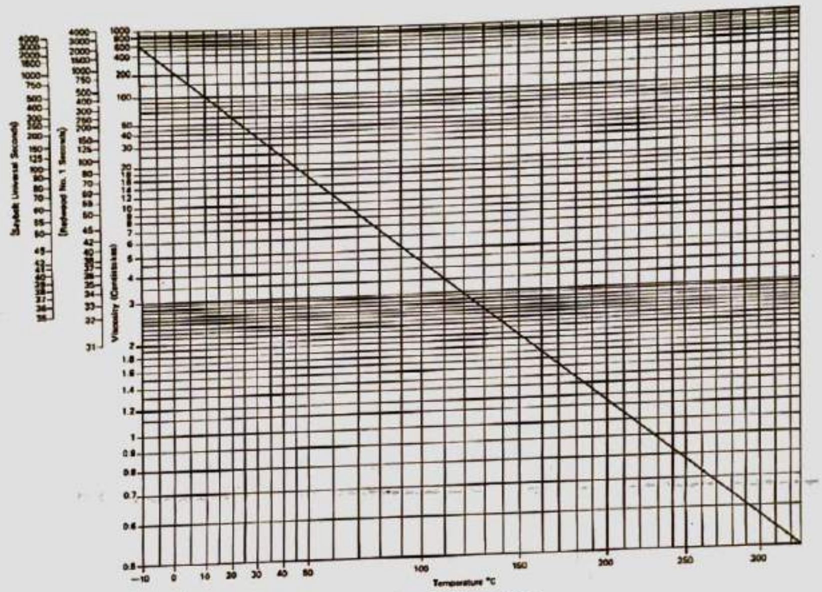
Relevant thermal physical properties of water and Shell Thermia Oil "B"

Table 1 Specific heat capacities of liquid water

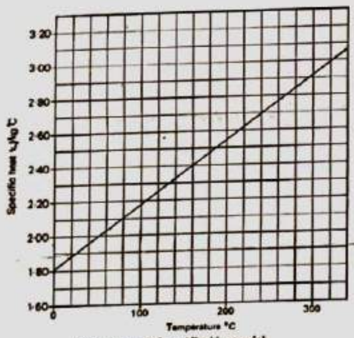
t (°C)	c_{pf} (kJ/kg·K)
5	4.204
10	4.193
15	4.186
20	4.183
25	4.181
30	4.179
35	4.178
40	4.179
45	4.181
50	4.182
55	4.183
60	4.185
65	4.188
70	4.191
75	4.194
80	4.198
85	4.203
90	4.208
95	4.213
100	4.219

Source: GFC Rogers and YR Mayhew, Thermodynamic and transport properties of fluids – SI Units, 4th ed., Basil Blackwell, 1980.

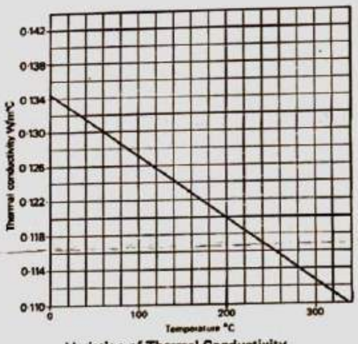
The thermal physical properties of Shell Thermia Oil "B" are shown in the next two pages.



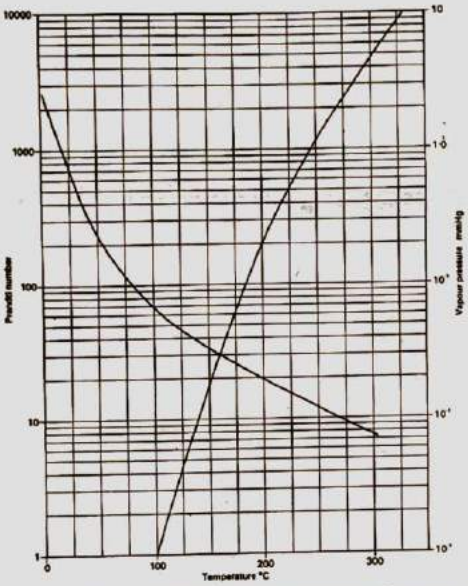
Variation of Viscosity with Temperature



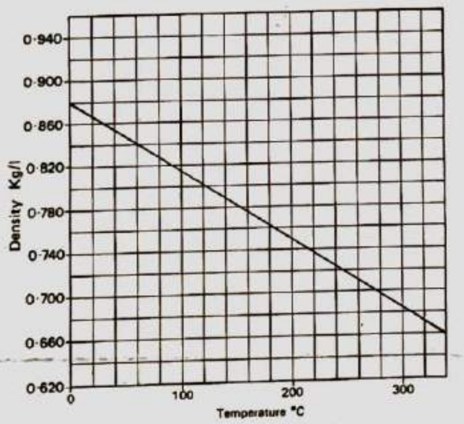
Variation of Specific Heat with Temperature



Variation of Thermal Conductivity with Temperature



Variation of Prandtl Number and Vapour Pressure with Temperature



Typical variation of Density with Temperature