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Thermal Fluid Application Lab- Part Two
ENMC 411

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Heat transfer
Experiment # 6 Extended surface conduction
Apparatus: Extended surface heat transfer apparatus/ Thermodynamic lab

Objectives:

- Verify Fourier law of conduction.
- Measure conductivity of metals
- Measure temperature profile along a rod.
- Apply fin theory
- Calculate heat losses from fin rod
- Calculate efficiency of fin
- Apply basic extended surface heat transfer.

Apparatus description:

The extended surface heat transfer apparatus comprises a long horizontal rod, which is heated at one end to provide an extended surface (cylindrical rod) for heat transfer measurements. Thermocouples at regular intervals along the rod allow the surface temperature profile to be measured. By making the diameter of the rod small in relation to the length, thermal conduction along the rod can be assumed to be one-dimensional and heat loss from the tip can be ignored.

The assembly consists of the control panel with read outs and control, and the extended surface or the cylindrical rod as shown in figure 1.

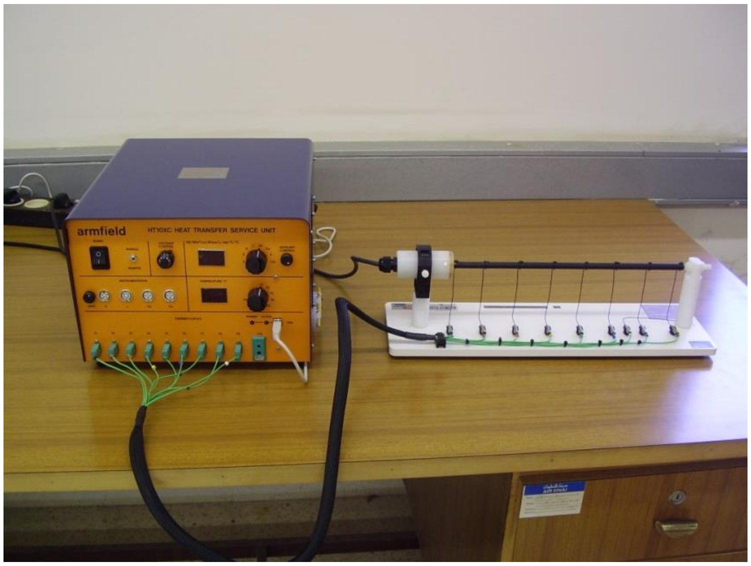


Figure 1: Extended heat transfer apparatus.

Heated rod

The bar is manufactured from a solid brass with a constant diameter of 10 mm and is mounted horizontally with support at the heated end. The bar is coated with black paint which provides a consistent emissivity close to one. The thermal conductivity of the bar is 121 W/m.K.

Heater

The rod is heated by a cartridge electric heating element operating at low voltage and is protected by a thermostat to prevent damage from overheating. The heating element is inserted co-axially into the end of the rod and is rated to produce 20 Watts nominally t 24 Volts DC. The power supplied to the heated rod can be varied and measured on the HT10X.

Thermocouples

Eight thermocouples are attached to the surface of the rod at equal intervals of 50 mm giving an overall instrumented length of 350 mm. Location of each thermocouple is shown in the apparatus. T1 measures the temperature at the hot end of the rod while T9 measures the ambient air temperature. All thermocouples are K type

The heater may be operated manually or remotely using the PC and the software.
For manual operation set the selector switch to the manual position. The voltage supplied to the heater is adjusted using the multi-turn potentiometer from 0 to 24 Volts DC.

The power supplied to the heater is the voltage times the current. Power = IxV Watts.
The temperatures can be read manually by the selecting switch set to the required position and read the value on the panel display. The temperature can be read by the Software and displayed on the mimic diagram of the HT15 software when on the REMOTE operation mode.

Experimental procedure

Part one (Manual)

1. Operate on the manual mode
2. Set the voltage control to 20 Volts. When T1 reaches 80 ^{o}C reduce voltage to 9 volts.
3. Record the temperature of all thermocouples.
4. Repeat every five minutes till reaching steady state (when readings of temperatures remain constant).

Part two (Software)

1. Select REMOTE setting, and set the voltage to zero Volts using the control box.
2. From the PC and software click **load** to start the program. Then go into **view** and schematic of rod - temperature. Enter into computer control and click *power on*.
3. From heater control adjust the heater to give 10 volts.
4. Go to **view** then *tables* click **Go** *to* see the temperatures, repeat this every 5 minutes until reaching steady state. Clicking *sample* then *next results*.
5. To view the graph click **view** then **graph**, adjust the *temperature axis*
6. Repeat at another voltage 14 Volts.
7. You can save your results as excel files and copy to the USB

Theory

Refer to heat transfer book for convection –conduction systems.

Rectangular or pin (circular) fins have constant cross section area A$_c$=const=A $\Rightarrow \frac{dA_c}{dx} = 0$

Base temperature T$_b$=T(x=0)
Fluid temperature T$_p$
Surface area $A_s = P_x$ or $dA_s = Pdx$

Where P: perimeter, then $\frac{dA_c}{dx} = 0$ and $\frac{dA_s}{dx} = P$ simplifying fin equation

$$\frac{d^2T}{dx^2} - \frac{h}{kA_c} P(T - T\infty) = 0$$

Let $\theta = T - T\infty = T(x) - t\infty \rightarrow \frac{d\theta}{dx} = \frac{dT}{dx}$

$$m^2 = \frac{hP}{A_c K}$$

$$\frac{d^2\theta}{dx^2} - m^2\theta = 0$$

General solution : $\theta(x) = c_1 e^{mx} + c_2 e^{-mx}$

constants c$_1$ and c$_2$ evaluated from first B.C at the base (x=0) where T=T$_b$

$T(x=0) = T_b$ and $\theta(x=0) = T_b - T_\infty = -\theta_b$

$$\theta_b = c_1 + c_2$$

Second B.C depends on physical condition at other end.

Case A: convection at the tip (x=0)

$$q_{conv} = q_{const_{x=L}} \Rightarrow hA_c(T_l - T_\infty) = -kA_c \frac{dT}{dx}_{x=L}$$

or : $h\theta(L) = -k \frac{d\theta}{dx}_{x=L}$

Case B: Negligible convection (insulated) tip

$$\frac{d\theta}{dx}_{x=L} = 0$$

Case C: finite temperature at tip $T(x=L) = T_l$ or $\theta(L) = \theta L$

Case D: very long fin $L \rightarrow \infty$ $\quad T \rightarrow T_\infty \Rightarrow \theta L \rightarrow 0$

Apply B-C 2 for case D:

$$\theta_l = 0 = c_1 e^{-\infty} + c_2 e^{\infty} \rightarrow c_2 = 0$$

B-C 1 : $c_1 + c_2 = \theta_b \Rightarrow c_1 = \theta_b$

Then $\theta = \theta_b e^{-mx}$

Total heat transfer from fin for case D

$q_f = q_{constatbase}$ from energy balance over entire fin

$$q_f = -kA_c \frac{dT}{dx}_{x=0} = -kA_c \frac{d\theta}{dx}_{x=0}$$

$$q_f = -kA_c\left[-m\theta_b e^{-m(0)}\right] = kA_c m\theta_b = kA_c\sqrt{\frac{hP}{kA_c}}\theta_b$$

$$q_f = \sqrt{hPkA_c}\theta_b$$

Fin efficiency = $\dfrac{q_f}{q_{\max}}$

q_f : Heat lost from fin

$q_{\max}$: Maximum possible heat from fin.

Maximum heat transfer from fin could occur if entire fin is at base temperature, where maximum driving for ΔT exist. Actually $T_{(x)}$ decrease along the fin and $T_{(x)} - T_\infty$ is decreasing.

$$\gamma_f = \frac{q_f}{hA_f\theta_b}$$

A_f : is the fin surface area.

Case B: adiabatic fin (no convection at tip)

Temperature distribution along the fin is given as:

$$\frac{(Tx - T9)}{(T1 - T9)} = \frac{\cosh m(L-x)}{\cosh mL}$$

T1 = base temperature, and T9 is the ambient temperature.

The heat transfer from the fin is given as;

$$q_f = \sqrt{hPkA_c}\theta_b \tanh(ml)$$

The fin efficiency is given as;

$$\gamma_f = \frac{\sqrt{hPkA_c}\theta_b \tanh(ml)}{hA_f\theta_b} = \frac{\sqrt{hPkA_c}\tanh(ml)}{hLP}$$

since $A_f = LP$

$$\gamma_f = \frac{\tanh(ml)}{L\sqrt{\frac{hP}{kA_c}}} = \frac{\tanh(ml)}{mL}$$

Heat transfer from a cylindrical rod:

$$q_{tot} = hA_s(T_s - T_\infty)$$

Where h is the combined convection and radiation heat transfer., T_∞ is the ambient air temperature, Ts is the surface temperature. As, is the surface area and is given by πDL.

The combined heat transfer coefficient $h = h_c + h_r$.

Where h_c is the convection heat transfer coefficient and h_r is the radiation heat transfer coefficient.

The convection heat transfer coefficient can be calculated using a simple relationship ;

$$h = 1.32\left(\frac{(Ts - T\infty)}{D}\right)^{0.25}$$

The average heat radiation coefficient is estimated using the relationship;

$$hr = \sigma\varepsilon\frac{(Ts^4 - T\infty^4)}{(Ts - T\infty)}$$

σ= 56.7x10^{-9}W/m^2.K^4

ε = 0.95

D = 0.01 m

L = 0.35 m

Analysis & calculations

1. In a table list the temperature in all locations (T1 to T9)
2. Plot the values of temperature at the various locations of the rod (T1 to T8).
3. Find the value of **m** in the fin profile. You can find value of **m** for each location by solving the distribution in each location. Then calculate an average value. You may try different values to get closer to the measure profile (starting value m=7.4).
4. Show both experimental and theoretical curves on the same figure.
5. Comment on the shape of the curve.
6. Would doubling the length of the rod double the lost heat from it? Why?
7. Calculate the heat lost from the rod from the power supplied to the rod?
8. Calculate the heat lost from the rod by the conduction at the base (heated end).
9. Estimate the convection and radiation coefficients and the heat transfer from surface at each thermocouple location.
10. Calculate the heat transfer using the theoretical equations for fins given in theory.
11. Compare the value of total heat lost from rod calculated by different methods, and comment on the difference and which one you think gives the best answer? Why?
12. Calculate the fin efficiency and compare it with theoretical values.

Heat transfer

Experiment # 7 Forced and Free Convection

Apparatus: Cross flow heat exchanger/ Thermo lab

Objectives:

- Measuring time dependent temperature of a rod
- Verify lumped capacitance method.
- Measure forced convection coefficient
- Investigating effect of air speed & flow on cooling rate
- Investigating effect of air speed on convection coefficient
- Measure free convection heat transfer coefficient

Apparatus description:

The set-up for this experiment is shown in Fig. 1.

The apparatus consists of the following:

1. Perspex working section through which air may be drawn by a centrifugal fan.
2. Perspex rods, inserted into the working section with their axes at right angles to the direction of flow.
3. A pure copper rod, 10 cm in length.
4. A cylindrical electrical heater which raises the temperature of element to a maximum of 80^{o}C.
5. Centrifugal fan driven by 1 hp electric motor.
6. The fan discharges to a graduated throttle valve by means of which the air velocity through the apparatus may be regulated.
7. A total head tube to permit exploration of the flow pattern upstream of the tube bank and this may be traversed in a direction perpendicular both to the air flow and to the axes of the element.
8. Static tapping so that the velocity head may be recorded by a manometer.
9. Inclined manometer for measurement of pressure drop and velocity heads.
10. Thermocouples in the element and at the air inlet are of copper and constantan for measurement of temperature difference.

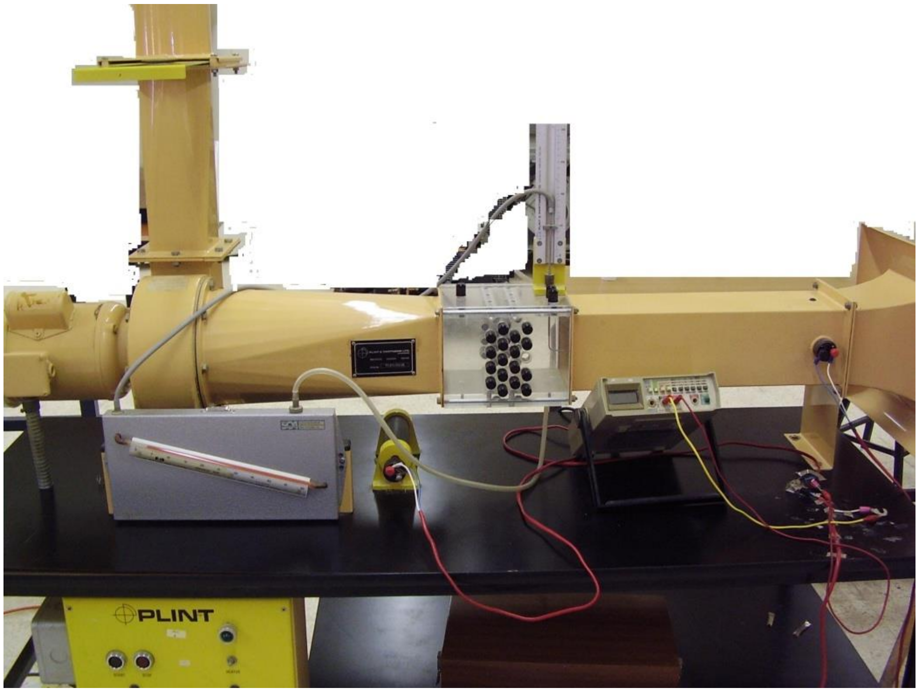


Figure 1: Cross flow het transfer apparatus

Experimental procedure

1. Make sure there are no perspex rods in the working station.
2. Set the throttle opening as (10%) open.
3. Insert the copper rod into the cylindrical heater.
4. Switch the cylindrical heater on.
5. When the temperature difference between the copper rod and the air temperature is in between 2.2 ~ 2.4 mV, remove the copper rod from the heater and place it in the center of the front raw.
6. Switch the fan on.
7. Once the copper rod is in place, read and record; time, t, temperature difference, $\Delta T = T - T_{\infty}$, every 10 seconds until the temperature difference reaches about 0.4 mV. In addition record air temperature, T_{∞}, and the velocity head, H_1.
8. Repeat the heating and the cooling of the rod for throttle openings of 20%, 40%, 60%, 80% and 100%.
9. For free convection repeat 1 through 3 above but don't switch the fan on, you may record temperature every 30 seconds.

Theory

Using the lumped capacity method for transient cooling, the following relation can be derived:

$$\ln\left[\frac{T-T_\infty}{T_o-T_\infty}\right]=-mt \quad ----(1)$$

$$where, m=\frac{hA_e}{\rho CV_e}$$

$$m=\frac{h}{\rho CL_s} \quad -----(2)$$

$$where,\ L_s=\frac{V}{A_e}$$

T : the temp. of the heated element, °C.
T_∞ : air temp., °C.
T_o : initial temp., °C.
t : time, seconds.
h : convective heat transfer coefficient, $\frac{W}{m^2.^o C}$
A_e : effective surface area of heated element, m^2.
r : density of heated element, kg/m^3.
C : specific heat, J/kg.°C
V_e : effective volume of heated element, m^3.
L_s : characteristic length, m

A certain amount of heat is conducted from the heated copper element into the plastic extension pieces. Due to this an addition to the true length of the heated element to give an effective length to be used in the calculations.

$$l_e = l + 0.0084$$

where : l : length of the copper heated element in m.
l_e : effective length of heated element in m.

For the lumped capacity system analysis to be valid, the value of the Biot number, Bi :

$Bi < 0.1$

where $Bi=\frac{hL_s}{K}$

K : thermal conductivity of the heated element, W/m. °C

Equation (1) represent the equation of a straight line, with a slope of -m. Plotting $\ln\left[\frac{T-T_\infty}{T_o-T_\infty}\right]$ vs. t, the slope of the line can be determined. Once the value of m is known, the convective heat transfer coefficient , h, may be calculated from equation (2).

The velocity, V, in the test section may be determined from the following relation :

$$V = 237.3\sqrt{\frac{H_1 T_\infty}{P_a}} \quad ----(3)$$

where, H_1 : upstream velocity head, cm H_2O
P_a : atmospheric pressure, N/m^2
T_∞ : absolute temp.

To determine the velocity of the flow in the transverse plane where the heated element is located, the conservation of mass is used:

$$\dot{m}_1 = \dot{m}_2$$

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2$$

$$but\, \rho_1 \rho_2$$

$$\therefore V_2 = \frac{A_1}{A_2} V_1$$

Note that, the diameter of the heated element and the perspex rods is 1.25cm, and the height of the working section is 12.5cm.

Nusselt number, Nu, is a non-dimensional heat transfer number and it is defined as:

$$Nu = \frac{hd}{K}$$

where: h : convective heat transfer coefficient
d : diameter of the heated element
K : thermal conductivity of air

Nusselt number is a function of parameters: Reynolds number, Re and Prandtl number, Pr
Defined as:

$$\mathrm{Re} = \frac{Vd}{\nu}$$

$$\mathrm{Pr} = \frac{C_p \mu}{K}$$

where: V : air velocity
d : heated element diameter
⍰ : kinematic viscosity of air
C_p : specific heat of air
K : thermal conductivity of air
⍰ : dynamic viscosity of air

Analysis & calculations

1. Plot $\ln\left[\frac{T - T_\infty}{T_o - T_\infty}\right]$ vs. time. For each of throttle opening of 10-100%.
2. Calculate heat transfer coefficient h for each opening.
3. Calculate Biot number and check the validity of the LCM

4. Calculate the air velocity and the Reynolds number for each opening.
5. Calculate the Nusselt number based on the experimentally found h.
6. Calculate the theoretical Nu from empirical forced convection correlation of a cylinder in cross flow: $Nu = 0.24\,(Re)^{0.6}$
7. Plot Nusselt number vs. Reynolds number. For both experimental and theoretical on the same graph.
8. From your experimental results obtain a correlation similar to the above one as Nu = f(Re)
9. Plot the transient heat flow vs. time for a typical case (e.g. 60% opening).
10. For free convection case repeat 1 through 5 above however use the free convection correlations for comparison with theoretical values. Remember you need Rayleigh number in this case.

Heat transfer

Experiment # 8 Heat exchanger

Apparatus: Heat exchanger/ Thermo lab

Objectives:

- Distinguish types of heat exchangers
- Apply basic heat exchanger theory
- Investigate flow arrangement (co and counter flows)
- Measuring log-mean- temperature difference
- Measuring the overall heat transfer coefficient U -value
- Effect of flow rate on the U-value
- Investigating heat exchanger efficiency.

Apparatus description:

The heat exchanger unit consists of a plate heat exchanger, heating reservoir, thermostat to control the hot water temperature, thermocouples that measure temperature of flowing liquid, a flow meter sensors and the data acquisition system, figure 1 shows the unit.

The connecting hoses can be easily unlocked and connected to the exchanger allowing easy change of flow arrangement form co current to counter current flow.

Figure 1 shows the experimental heat exchanger.

Experimental procedure

Priming:

1. To priming the hot and cold water circuits connect the heat exchanger hot water inlet (appropriate flexible tube with red collar) to the quick release cold water outlet connector (blue collar with arrow pointing left) at the rear of HT30X.
2. Connect the heat exchanger hot water outlet (appropriate flexible tube with red collar) to the quick release hot water inlet connector on HT30X (red collar with arrow pointing right at the front of HT30X.
3. To prime the hot water circuit first ensure the by pass valve in the hot water circuit is fully closed (right-hand valve with black handle 90 degree to valve body).
4. Ensure that the cold water pressure regulator is set to minimum pressure (pull the grey knob upwards – towards the right – the turn the knob fully anticlockwise, looking at the end of the knob).
5. Open the cold water pressure regulator valve fully (left-hand valve with black handle in line with valve body). Gradually adjust the pressure regulator by turning the grey knob clockwise until cold water is heard / seen to flow steadily through the flexible tubing of the hot water circuit.
6. wait until water flows in to the clear plastic priming vessel and all air bubbles have been expelled from flexible tubing. ***Note:*** water will flow from the hot water outlet connector at the front of HT30X before priming is complete, this is normal and the water will drain in the central canal.
7. When the system has primed, close the cold water flow control valve (left hand valve with black handle at 90 degrees to valve body).
8. Disconnect the flexible tube (to the heat exchanger) from the cold water outlet connector (blue collar with arrow pointing left) then reconnect the same flexible tube to the hot water outlet connector (red collar with arrow pointing left).
9. Fill the clear plastic priming vessel with clean water to the level of over flow the replace the lid on vessel.
10. Switch on the hot water circulating pump. Any remaining air bubbles will be expelled via the priming vessel. Open and close the hot water bypass valve (right-hand valve with black handle) several times until no air bubbles are seen traveling along the flexible tubing. If the level falls below mid height in priming vessel the it will be necessary to top it up with clean water.
11. Reconnect as in figure 1.

Cocurrent

1. Close the cold water flow control valve V_{cold} the reverse the cold water connections to the shell of the heat exchanger. Note : the connection to the heat exchanger are now configured for cocurrent operation where the hot and cold water fluid streams flow in the same direction across the heat transfer surface (the two fluid streams enter the heat exchanger at the same end). See figure 2.
2. Open the cold water control valve V_{cold} and adjust it to give a reading of 1 liter/min (hot and cold water flow rates the same as before).
3. when the temperature are stable record the following: T_1,T_2, T_3, T_4, F_{hot}, F_{cold}.
4. Check the cold fluid flow rate by collecting certain amount of water in graduated cylinder and dividing by the time it took to collect this amount of water.

5. Repeat for another 4 flow rates of the hot/cold water.

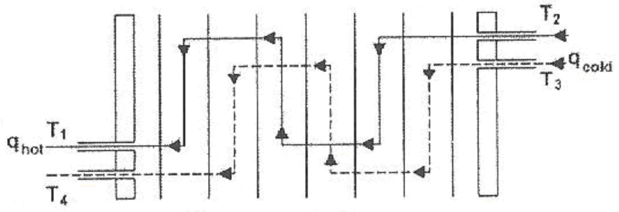
Counter current

1. Set the temperature controller to a set point approximately 45°C above the cold water inlet temperature (T_4) . (e.g If T_3 = 15°C the set controller to 60°C, then switch the hot water circulator.
2. Set the flow indicator switch to F_{cold} then adjust the cold control valve V_{cold} (not the pressure regulator $V_{reg)}$ to give 1 liter/min.
3. Set the flow water indictor switch to F_{hot} then adjust the hot water control valve V_{hot} to give 2 liters/min.
4. Allow the temperature to stabilize (monitor the temperature using the switch / temperature meter).
5. When the temperature are stable record the following: T_1, T_2, T_3, T_4, F_{hot}, F_{cold}.
6. Repeat experiment for another 4 flow rates of hot/cold water.

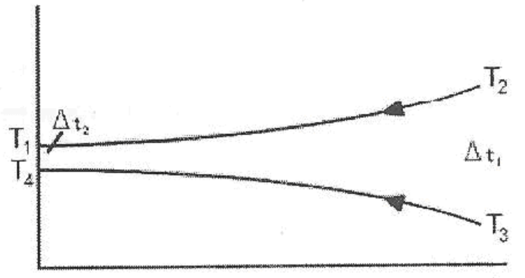
Theory

When the heat exchanger is connected for countercurrent operation the hot cold fluid streams flow in opposite directions across the heat transfer surface (the two fluid streams enter the heat exchanger at opposite ends). Figures 2 and 3 are showing the co-current and counter-current arrangements and their temperature profiles.

The hot fluid passes through the seven tubes in parallel, the cold fluid passes across the tubes three times, directed by the baffles inside the shell.

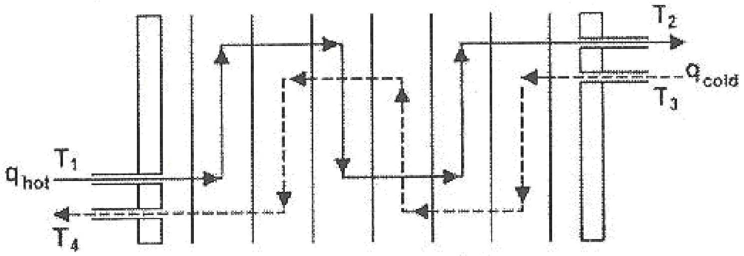


Cocurrent diagram

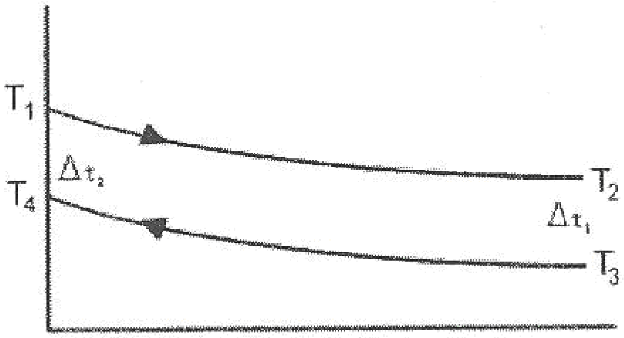


Cocurrent

Figure 2: Co-current arrangement and its temperature profile.



Countercurrent Diagram



Countercurrent

Figure 3: Countercurrent arrangement and its temperature profiles.

Because the temperature difference between the hot and the cold fluid streams varies along the length of the heat exchanger it is necessary to derive an average temperature difference (driving force) from which the heat transfer calculations can be performed. This average temperature difference is called the Logarithmic Mean Temperature Difference (LMTD) Δt_{1m}

Where

(LMTD) $\Delta t_{1m} = [(\Delta t_1 - \Delta t_2) / \ln (\Delta t_1 / \Delta t_2)]$

And

$\Delta t_1 = (T_1 - T_4)$, $\Delta t_2 = (T_2 - T_3)$ (°C)

<u>Note</u> this equation cannot produce any results for the case where $\Delta t_1 = \Delta t_2$

(LMTD)

$\Delta t_{1m} = [(T_1 - T_4) - (T_2 - T_3)] / \ln[(T_1 - T_4) / (T_2 - T_3)]$ (°C)

In this experiment the equation for LMTD is the same for both countercurrent and cocurrent operation because the temperature measurement points are fixed on the exchanger. Two different equations will result if the temperature points are related to the fluid inlets and outlets.

Heat transfer in the exchanger is given by the equation;

$Q = UA\,F\,\Delta t_{1m}$

Where U is the overall heat transfer coefficient

A area of heat exchange
F correction factor for shell in tube equals 0.95
Δt_{1m} is the log –mean temperature – difference.

The heat exchange area for the shell and tube exchanger must be calculated using the arithmetic mean diameter of the inner tubes.

Arithmetic mean diameter	$d_m = (d_o + d_i) / 2$	(m)
Heat transmission length	$L = n \, . \, s$	(m)

Where

n = number of tubes = 7
s = heat transmission length of each tube = 0.144 (m)

$L = 1.008$

Heat transmission area $A = \pi \, . \, d_m \, . \, L$ (m^2)

For plat heat exchanger the total area of all plates is 0.4 m^2

Also the heat exchanged can be calculated based on the heat lost by the hot fluid or the heat gained by cold fluid as
$Q = mC(\,T_{out} - T_{in})$

It is known that's the reduction in the hot fluid temperature
$T_{hot} = T_1 - T_2$ (°C)

And the increase in the cold fluid temperature
$T_{cold} = T_4 - T_3$ (°C)

And the heat power emitted from fluid
$Q_e = m_h \, . \, (Cp)_h \, (T_1 - T_2)$ (in Watt)

Where:

Hot fluid inlet temperature	T_1	(°C)
Hot fluid outlet temperature	T_2	(°C)
Cold fluid inlet temperature	T_3	(°C)
Cold fluid outlet temperature	T_4	(°C)
Hot fluid volume flow rate	V_{ho}	
Specific heat for hot fluid	$(Cp)_h$	(kJ/kg °K) from table 1
Mass flow rate (hot fluid)	m_h	(kg/s)

A useful measure of the heat exchanger performance is temperature efficiency of each fluid stream, the temperature change in each fluid stream is compared with the maximum temperature difference between the two fluid streams given a comparison with an exchanger of infinity size.

Temperature efficiency for hot fluid

$\eta_h = [(T_1 - T_2) / (T_1 - T_3)] \times 100$ (%)

Temperature efficiency for cold fluid

$\eta_c = [(T_4 - T_3) / (T_1 - T_3)] \times 100$ (%)

Mean temperature efficiency

$\eta_m = (\eta_h + \eta_c) / 2$ (%)

Analysis & calculations

1. In a table present your results as flow rates of hot and cold fluids, temperatures of all streams, for both cases co and counter current arrangements.
2. Calculate the log mean temperature differences, the overall heat transfer coefficient, U.
3. Calculate the hot fluid, cold fluid, and average efficiencies for all runs.
4. Plot efficiencies versus cold /hot fluid flow rates, comment on results.
5. Plot U –value versus cold/hot fluid flow rates, comment on results.
6. Discuss the difference between the co and the counter current arrangements.

Thermodynamics
Experiment # 9 Refrigeration & cooling
Apparatus: Air cooler-heat pump/ Thermo lab

Objectives:

- Know components of a vapor compression cycle
- Distinguish cooling and heating modes of heat pump
- Measuring cooling/ heating capacity of the unit
- Measuring COP of the unit
- Investigate effect of heat removal on unit performance
- Determining air properties and the use of psychrometric chart

Apparatus description:

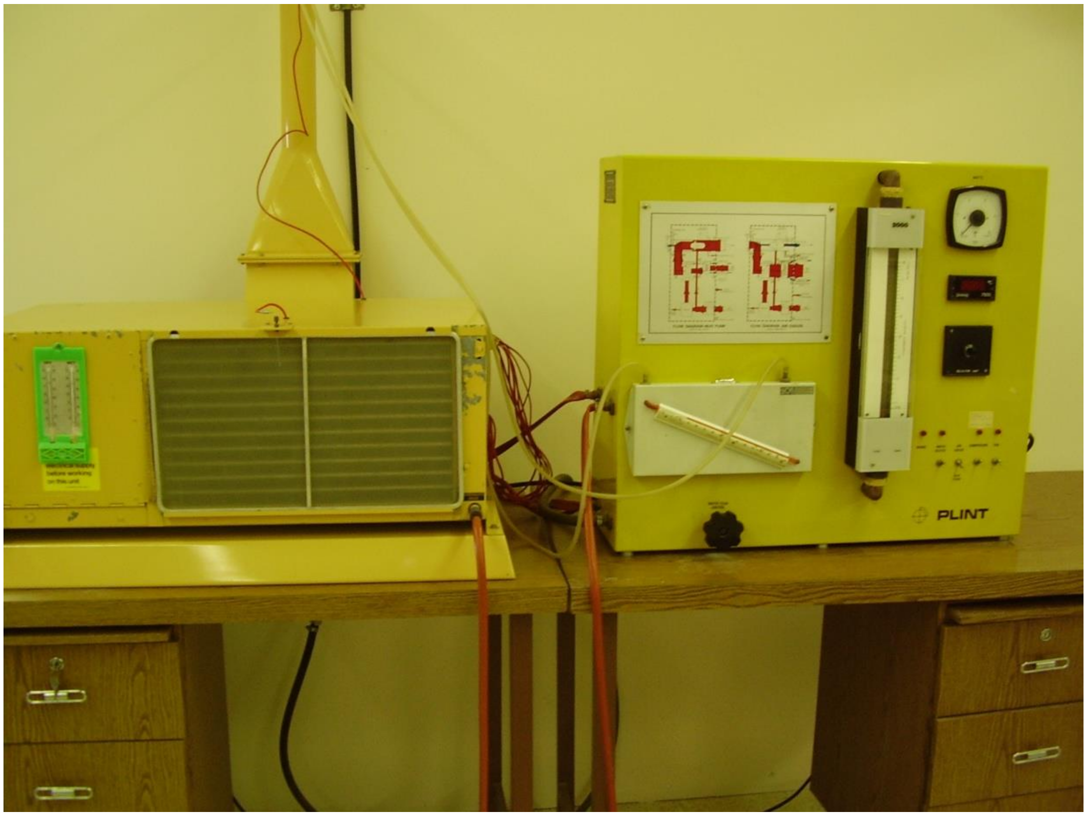


Figure 1: Heat pump unit

<u>Experimental procedure</u>

<u>Heat pump</u>

1. Turn on the circulating water and adjust the flow rate to a value of 4 liter/min using rotameter.
2. Read the inlet circulating water, T_3.
3. If T_3 is less than 10°C, switch the water heater on.
4. Choose heating to operator as a heat pump.
5. Switch on the compressor and the fan. Note : The wattmeter reading is the total electrical power input to both the fan and the compressor. To get the input power to the individual units, switch off the fan momentarily at which the wattmeter reading is the input power to the compressor.
6. Every 5 minutes, read and record the following : The temperatures T_1, T_2, ..., T_{10}, pitot tube velocity head, H_1, the total input power to the compressor and the fan, E_{total}, the input power to the compressor, E_c.
7. Measure the relative humidity φ of air entering the unit using the sling hygrometer.
8. When steady state condition is recorded (i.e., the temp. is not changing any more). Check T_2 only !
9. Adjust the circulating water flow rate to 2 liter/min and wait approximately 5 minutes and then read and record only once all the values you recorded in step 6.
10. Repeat step 9 for circulating water flow rates of 3, 5 and 6.

<u>Air cooler</u>

1. Select the cooling mode.
2. Run the unit until reaching steady state at a water flow rate of 4 L/minute.
3. Change flow rate to 2, wait for 5 minutes and record all parameters,
4. Repeat for another flow rate at 6 L/minute.

Theory

The notation below is used in the theory explained in this experiment.

Temperatures

T_1	Air at inlet
T_2	Air at discharge
T_3	Circulating water at inlet
T_4	Circulating water at discharge
T_5	Compressor discharge
T_6	Compressor inlet
T_7	Refrigerant-to-water heat exchanger discharge
T_8	Refrigerant-to-water heat exchanger inlet
T_9	Refrigerant-to-air heat exchanger inlet
T_{10}	Refrigerant-to-air heat exchanger discharge

Mass Flow Rates

Dry air	m_1 kg/s
Circulating water	m_3 kg/s

Thermal Quantities

Specific heat of water	C_w J/kg °C
Specific heat of air at constant pressure	C_p J/kg °C
Specific enthalpy of water vapour	h_v J/kg

Enthalpy Flow Rates

Dry air entering conditioner	Q_1 J/s
Water vapour entering conditioner	Q_2 J/s
Dry air leaving conditioner	Q_3 J/s
Water vapour leaving conditioner	Q_4 J/s
Circulating water at inlet	Q_6 J/s
Circulating water at outlet	Q_7 J/s
Radiation and stray losses	Q_8 J/s

Electrical Input

Refrigerator compressor	E_c W
Fan	E_F W

Psychrometer Data

Relative humidity at inlet	Φ
Density of saturated water vapour at inlet	ρ_w kg/m^3
Density of dry air at inlet	ρ_a kg/m^3
Specific humidity at inlet	γ

Ideal Heat Pump

Power input	W J/s
Input from cold source	q_2 J/s
Output to hot sink	q_1 J/s

The machine is shown schematically in Fig.3, which shows the various energy flows through the system boundary. They are defined as below :

Enthalpy of dry air entering conditioner

$$Q_1 = m_1 C_p T_1$$

Enthalpy of water vapour entering conditioner

$$Q_2 = \gamma m_1 h_v$$

Enthalpy of dry air leaving conditioner

$$Q_3 = m_1 C_p T_2$$

Enthalpy of water vapour leaving conditioner

$$Q_4 = \gamma m_1 h_v$$

Enthalpy of circulating water at inlet

$Q_6 = m_3 T_3 C_w$

Enthalpy of circulating water at outlet

$Q_7 = m_3 T_4 C_w$

Radiation and stray losses

Q_8

Electrical input to fan

E_F

The Steady flow energy balance for the system :

$$(Q_6 - Q_7) + (E_c + E_F) = (Q_3 + Q_4) - (Q_1 + Q_2) + Q_8$$

The coefficient of performance, COP, may be defined in two different ways :

1. The overall of external coefficient

$$COP_{external} = \frac{(Q_3 + Q_4) - (Q_1 + Q_2)}{(E_c + E_F)}$$

The corresponding ideal value,

$$COP_{external)ideal} = \frac{\frac{1}{2}(T_1 + T_2)}{\frac{1}{2}(T_1 + T_2) - \frac{1}{2}(T_3 + T_4)}$$

2. The internal coefficient :

$$COP_{\text{int}ernal} = \frac{(Q_3 + Q_4) - E_F - (Q_1 + Q_2)}{E_c}$$

The corresponding ideal value,

$$COP_{\text{int}ernal)ideal} = \frac{T_{10}}{T_{10} - T_8}$$

The air flow through the unit is measured using a pitot-static tube mounted in the center of the discharge duct.

The volumetric flow rate, $\dot{V}$, of air in the duct :

$$\dot{V} = 0.3014\sqrt{\frac{H_1 T_2}{P_a}}\ m^3/s$$

Where :

H_1 : velocity head in mm H_2O

T_2 : absolute air temp. at discharge

P_a : atmospheric pressure, N/m^2

The mass flow rate, m_1, of air in the duct :

$$m_1 = 0.00105\sqrt{\frac{H_1 P_a}{T_2}}\ kg/s$$

The specific humidity of the air entering the unit :

$$\phi = \frac{\Phi \rho_w}{\rho_a}$$

Where :

Φ : relative humidity
ρ_w : density of saturated water vapour entering the unit
ρ_a : density of air entering the unit

When the device is reversible (i.e. operating in Carnot cycle) as shown in Fig.4, which is considered the ideal cycle.

The coefficient of performance of a heat pump, COP_{hp}, is defined as :

$$COP_{hp} = \frac{q_2}{W}$$

Where :

q_2 : is the input from a cold source
W : power input

$$q_2 = (Q_3 + Q_4) - (Q_1 + Q_2)$$

$$W = (W_c + W_F)$$

When the unit is operating in a Carnot cycle (i.e., ideal), the ideal coefficient of performance for heat pump is defined as:

$$COP_{hp)\,ideal} = \frac{T_2}{T_2 - T_3}$$

Analysis & calculations

For both cases heat pump and air cooling:

1. Plot T2, compressor power versus time, and comment on the curve.
2. Find inlet and exit air specific humidity using equations and psychrometric chart, also find for inlet air the specific volume, and enthalpy.
3. Calculate the volumetric flow rate of air in the duct.
4. Calculate the mass flow rate of air in the duct.
5. Calculate the heat added or removed from air.
6. Calculate the heat from circulating water.
7. Calculate the heat lost to surroundings.
8. Find the actual and ideal of both the overall external and the internal coefficients of performance.

Internal combustion engine
Experiment # 10 Diesel engine
Apparatus: Diesel test bed/ ICE lab

Objectives:

Overall objective is to test the performance of the Diesel engine. Specific objectives of the experiment include:

- Get to know main components of a diesel engine
- Measure torque and power of engine
- Measure fuel consumption of engine
- Calculate the specific fuel consumption of engine
- Plot torque and power curves versus engine speed
- Measure the air consumption
- Calculate air fuel ratio
- Calculate thermal efficiency of the engine.

Apparatus description:

The main components of the test bed are:
Universal support frame
Hydraulic dynamometer
Control pane; for air and fuel flow measurements
Water cooling system

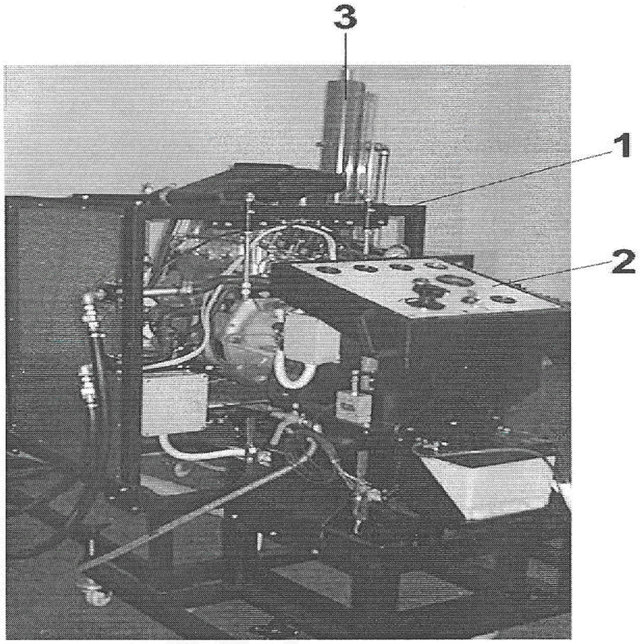


Figure 1 Diesel test bed.

3.1 Universal support frame consists off:

- Support frame for test engine
- Electrical cable connector
- Engine tested
- Braking system
- Load cell
- Exhaust manifold

3.2 Hydraulic dynamometer

Hydraulic dynamometer is made up of a dynamometer, wheel –mounted support frame and a control panel. It can be coupled to the test engine regardless of its type.

3.3 Control panel

As shown in figure it includes

Coolant temperatures
Oil temperature
Oil pressure
Vacuum meter
Braking action
Key operated ignition

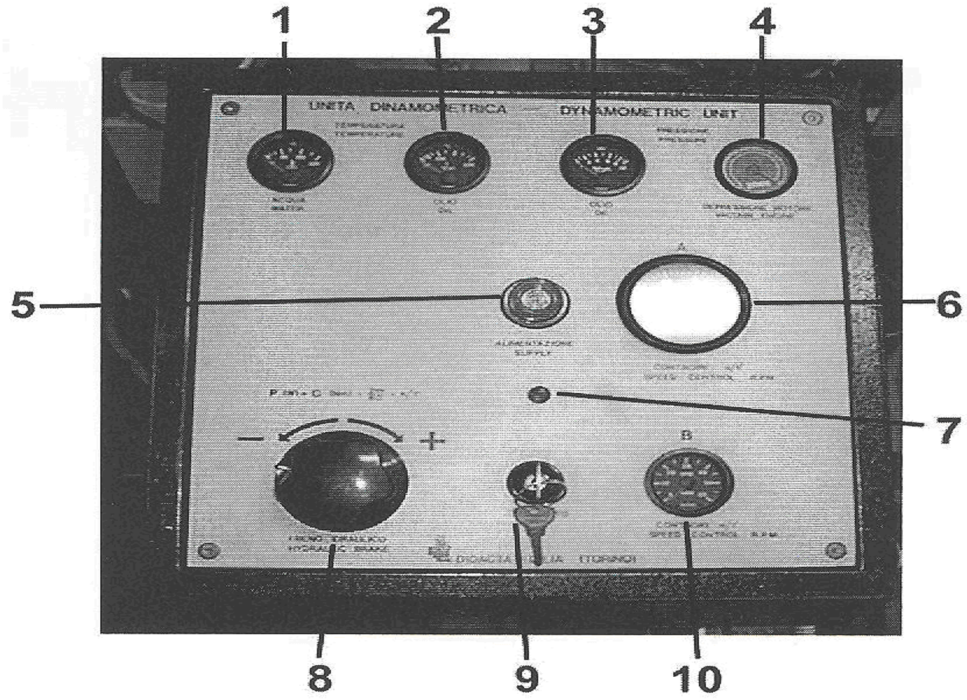


Figure 2 Control panel.

3.4 Water cooling system

The water cooling system keeps the water temperature below some set temperature with the aid of a thermostat controlled valve. The valve opens enabling cold water to flow into the column and mix with the contained water resulting in decreasing the temperature.

3.5 Air flow and fuel flow measuring system

The air and fuel flow measuring system makes it possible to determine the quantities of air and fuel consumed by the engine.

Air flow is measured by means of a manometer and a calibrated flange and orifice, the air flow as volume or mass flow can be read from the chart based on the manometer reading.

The fuel flow is measured by means of graduated burette. The quantity of used fuel by the engine is determined by dividing quantity of fuel consumed by the time it takes to consume this fuel quantity. When timing the fuel consumption close the valve that supplies diesel from the tank.

4. Starting the engine testing system

Check the functionality of the coolant circuit
Check the functionality of the fuel circuit
Check the functionality of the electrical connections
Check the functionality of the battery
Check the oil level
Check the fuel level
Check the water level
Start the cooling water
Adjust the water flow rate to 200-300 liter/hour
Open the fuel feed
Turn on the data acquisition unit
Start the motor by turning the key in the control panel
Set the throttle valve at minimum.

Apply small load by means of the hydraulic brakes to adjust engine speed to 1500 rpm.
Check the thermostat controlled valve on the cooling system setting 85-90 ^{o}C.

When temperature of water reached operating value you can start the testing process.

Make sure when the oil in the sump reaches and exceeds the operating temperature the cooling fan located under the engine turns on.

Experimental procedure

- Start the engine and take it to the required temperature. (as explained above)
- Set the throttle valve at value specified by instructor (5, 12.5, 25,), decrease the breaking torque to the minimum so to obtain highest possible rotation speed.
- Record the torque and the rpm read the manometer and convert it to volume and mass flow rates using the curves on the panel.
- Close the tank valve and time the consumed fuel.

- Increase the braking torque so to decrease the rpm in steps of 100 rpm each time (or as asked by instructor) recording: torque, rpm, air flow and fuel consumption, continue till maximum torque is reached.
- Now gradually decrease the load to obtain an increase in the rpm again in steps of 100 recording the rpm and the torque, air flow, and fuel flow until reaching the minimum torque.
- Repeat the experiment at another two throttle valve settings.
- Measure temperature and pressure in the lab.

<u>Theory</u>

Power P can be calculated from the torque and the angular velocity as:

$P = M^* n / 9549.3$
Where power in kW, torque in Nm, n in rev/minute

Fuel measurement is carried out by measuring time interval taken to consume known volume of fuel as,

$C = (V/t)\rho$

Where V fuel volume read from the burette
t time as measured by stop watch.
ρ fuel density

Specific fuel consumption is calculated as fuel consumption rate divided by power

Air to fuel ratio is calculated as,

AF = air flow rate / fuel flow rate
AF can be mass or mole ratios depending on the units used for flow.

Thermal efficiency is defined as specific output engine power divided by the fuel calorific value.

η =Power/(fuel flow rate * heating value)

Refer to thermodynamic text book for theoretical diesel cycle efficiency.

<u>Analysis & calculations</u>

1. Write down in a table: rpm, torque, manometer readings, air volume and mass flow rates, diesel consumed and time for its consumption.
2. Calculate the average value at each rpm, and then calculate the power, air fuel ratio, and specific fuel consumption.
3. Plot the torque and power versus rpm, and locate the maximum values.
4. Plot the specific fuel consumption versus speed for all throttle settings.

5. Plot the engine efficiency versus speed for all throttle settings.
6. Compare above curves with expected ones (theoretical) and comment on the deviation.
7. Convert power to power in standard air (760 mm Hg, 288 K) using the following equation:
   $P\ \text{std} = P\ (760/\ \text{pressure}) * (\surd\ T/288)$