ENERGY SYSTEMS ENGINEERING

COMBINED CONVECTIVE AND RADIATIVE HEAT TRANSFER

EXPERIMENT MANUAL

OBJECTIVE

Objective of this experiment is to investigate natural and forced convective and radiative heat transfer mechanisms for a horizontal cylinder; and observe the effect of surface temperature and flow velocity on convection and radiation.

THEORY

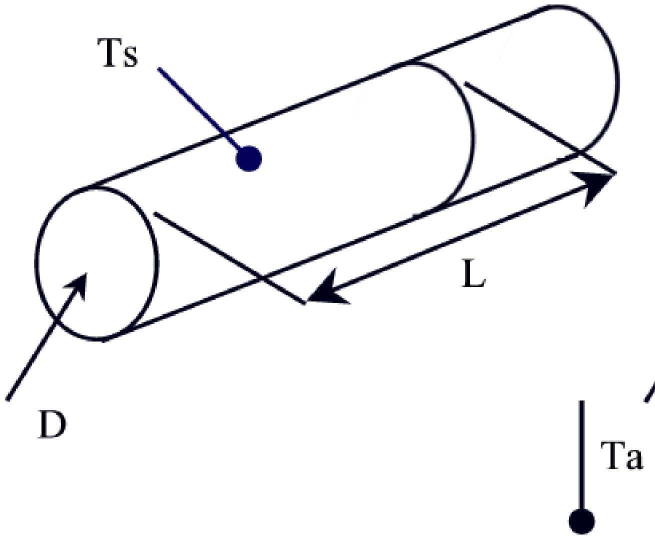


Figure a

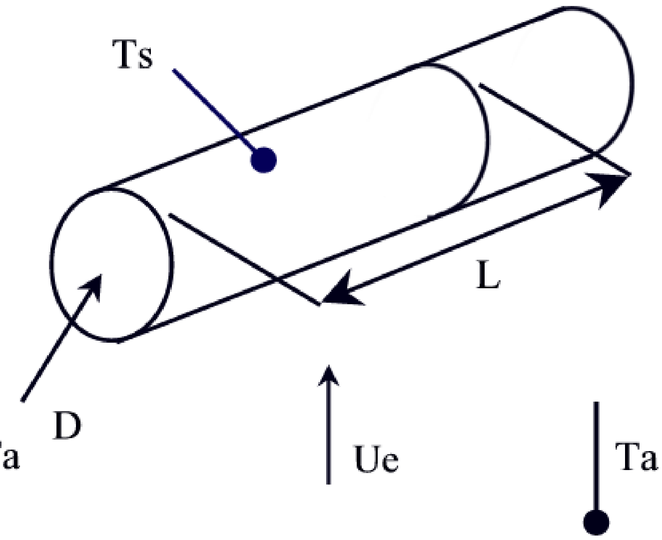


Figure b

If a cylinder of diameter D and heated length L is at a temperature T_s that is above that of the surrounding air T_a then the air immediately adjacent to the cylinder will start to warm, see Figure a. This will reduce its density and the air will flow upward due to buoyancy. In the absence of any outside influence such as draughts etc. this will set up a flow process where cooler air flows in from adjacent to the cylinder is warmed and flows upward from the cylinder. The buoyant flow process will transfer heat to the air and is referred to as natural convective heat transfer.

If a cylinder of diameter D and heated length L is at a temperature Ts is placed in an air stream of velocity Ue then heat will be transferred from the cylinder to the air stream, see Figure b. The convective heat transfer occurring with aid of an external fluid flow is referred as forced convection. The rate of forced convective heat transfer from the cylinder will be affected by the air velocity, the degree of turbulence in the air approaching the cylinder and the surface temperature of the cylinder. Compared with the same cylinder in still air, the rate of heat transfer due to forced convection will be higher and result in a lower surface temperature under the same power input conditions.

The cylinder will not only lose heat due to convection but also due to radiation. If the surface temperature Ts is sufficiently high then the radiant component can become a significant proportion of the heat transfer method. At relatively low cylinder temperatures convection will be the predominant heat transfer method though some heat will also be transferred due to radiation to the surroundings. If the cylinder surface temperature is raised further then the flow of air due to and causing convective heat transfer will increase but a greater proportion of heat will be lost from the surface due to radiation. The proportion lost due to radiation will depend upon the surface temperature of the cylinder, the emissivity of the cylinder, the emissivity of the immediate surroundings and the ambient temperature of the surroundings.

The heat lost due to natural convection, Q_{nc} can be determined from

$$Q_{nc} = h_{nc} A_s (T_s - T_a)$$

where h_{nc}: Overall heat transfer coefficient. due to natural convection
A_s: Heated surface area of the cylinder

For the natural convection from the cylinder, there are various equations. One is shown below that utilises non-dimensional relationships.

$$h_{nc} = \frac{k\ Nu_D}{D}$$

where k: Thermal conductivity (W/mK)
D: Diameter of the cylinder (m)
Nu_D: Nusselt number for the configuration

Nusselt number for cylinders in cross flow can be estimated as follows

$$Nu_D = c(Ra_D)^n$$

where Ra_D: Rayleigh Number ($Ra_D = Gr_D \cdot Pr$)
Gr: Grashof Number
Pr: Prandl Number
c: Coefficient
n: Coefficient

The coefficients may be determined based upon the calculated Rayleigh Number. The table showing the coefficients with respect to Ra_D can be found in chapter 9 in Fundamentals of Heat and Mass Transfer by T.L. Bergman 7th edition. Note that thermophysical properties of air are taken at film temperature.

The heat lost due to forced convection, Q_{fc} can be determined from

$$Q_{fc} = h_{fc} A_s (T_s - T_a)$$

where h_{fc}: Overall heat transfer coefficient due to forced convection

The forced convection coefficient can be determined for particular geometric configurations from a non-dimensional relationship. Similar to natural convection, dimensionless following relation can be written

$$h_{fc} = \frac{k\ Nu_D}{D}$$

For forced convection coefficient h_{fc} there are various non-dimensional equations of various complexity. These are the result of extensive tests on cylinders of various diameters at various operating conditions of air velocity and surface temperature. The resulting heat transfer coefficients are analysed non-dimensionally to develop a general equation for the geometric configuration. One such equation for cylinders in cross flow is as follows,

$$Nu_D = 0.3 + \frac{\left(0.62 {Re_D}^{0.5} Pr^{0.33}\right)}{\left[1 + \left({}^{0.4}/_{Pr}\right)^{0.66}\right]^{0.25}} \left[1 + \left({}^{Re_D}/_{282000}\right)^{0.5}\right]$$

where Re_D: Reynolds Number ($Re_D = \frac{Ue\ D}{\nu}$)

Note that for Nusselt Number correlation for forced convection, thermophysical properties of air are taken at stream temperature.

The measured duct velocity Ua is locally increased around the cylinder to Ue due to the blockage effect of the cylinder itself. This relates to the area ratio between the duct cross sectional area and the plan area of the cylinder in the duct. For this experimental set up, Ue can be calculated as,

$$Ue = 1.22\ Ua$$

When both forced convection and natural convection is present, usually one of them dominates the convective heat transfer. Natural convection is negligible if $(Gr_D / Re_D^2) << 1$ and that forced convection is negligible if $(Gr_D / Re_D^2) >> 1$.

Similar to convection, the radiant heat transfer component may be determined from

$$Q_r = h_r A_s (T_s - T_a)$$

where h_r: Overall radiative heat transfer coefficient

The overall radiative heat transfer coefficient may be determined from

$$h_r = F\ \varepsilon\ \sigma\ \frac{\left(T_s{}^4 - T_a{}^4\right)}{(T_s - T_a)}$$

where σ: Stefan Boltzmann Constant = 5.67 x 10^{-8} W/mK
ε: Emissivity of surface
F: View or shape factor that depends upon the surrounding geometry relative to the heat emitting body.

View factor and emissivity of the cylinder can be taken as 1 in calculations.

If the overall heat transfer coefficients in each case can be determined then the total heat transfer from the cylinder Q_{tot} may be determined from

$$Q_{tot} = Q_r + Q_c$$

where Q_c is the rate of heat transferred by dominant convective heat transfer mechanism.

EXPERIMENTAL SETUP

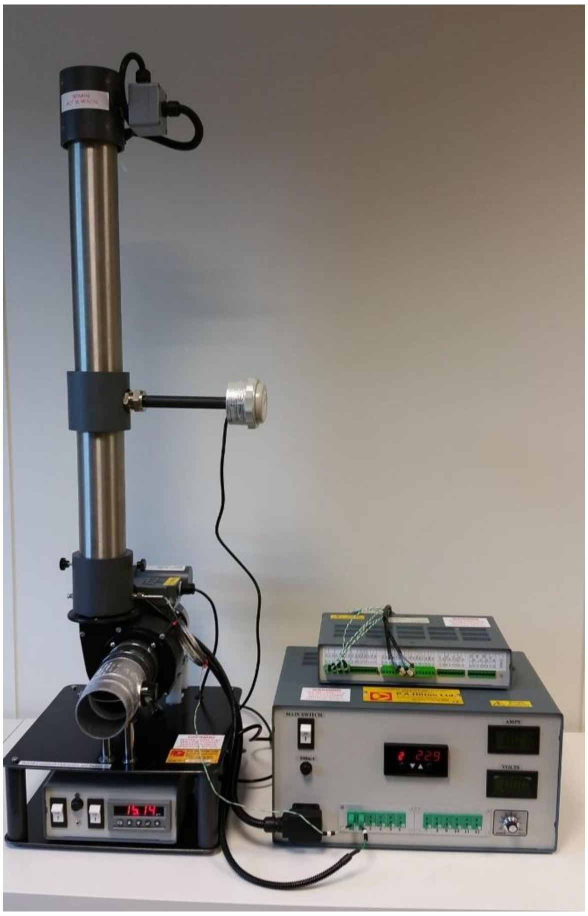
The experimental set-up comprises a cylindrical duct mounted on the discharge of a base mounted centrifugal fan. At the top of the duct is mounted an electrically heated cylinder. The dimensions of the cylinder is

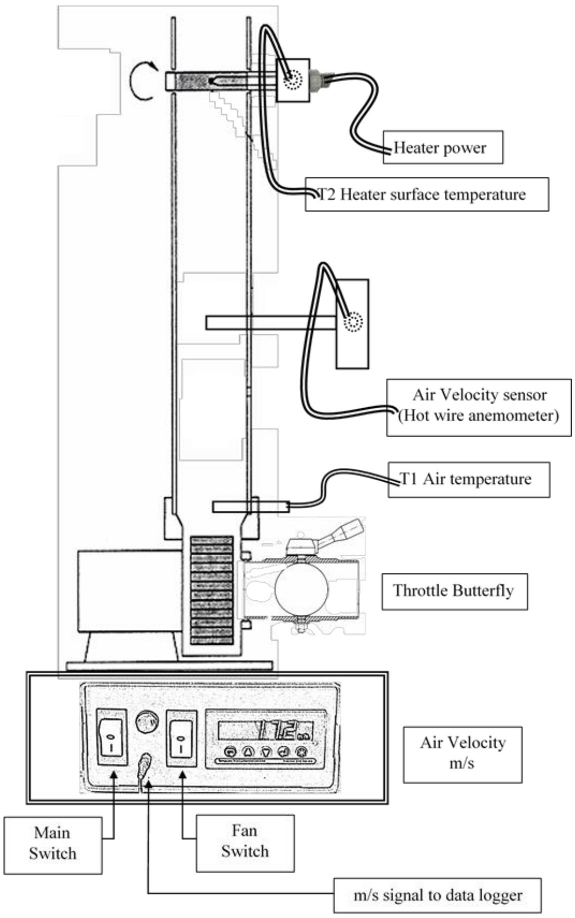
Diameter : 0.01 m
Heated length : 0.07 m

The mounting arrangement of the cylinder ensures that heat loss by conduction to the wall of the duct is minimised. A thermocouple (T2) attached close to the surface of the cylinder provides a temperature measurement. The thermocouple T2 connects to the Heat Transfer Service Unit H112 using a miniature 2-pin plug. The surface of the cylinder is coated with a matt black heat resistant finish which give an emissivity close to 1.0

The free stream air temperature (T1) is recorded by a duct-mounted thermocouple. This connects to the Heat Transfer Service Unit using a miniature 2-pin plug. The power supplied to the heated cylinder is provided (and measured) by the Heat Transfer Service Unit through the power conduit terminating with an 8-pole plug.

The air velocity passing the cylinder can be varied from zero to more than 8m/s depending upon the local mains voltage and supply frequency. The hot-wire anemometer is permanently mounted in the duct and connects to the console below using a line plug and socket. The air





velocity is controlled by the use of an intake Butterfly Valve. For natural convection experiments, the fan may be switched off using the Fan Switch on the console below. The free stream air temperature (T1) is recorded by a duct-mounted thermocouple. This connects to the Heat Transfer Service Unit H112 using a miniature 2-pin plug.

EXPERIMENTAL PROCEDURE

1. Plug in the thermocouples and heater connection to Heat Transfer Service Unit.
2. Turn on the Heat Transfer Service Unit
3. Adjust the voltage given to the heater by turning the button on Heat Transfer Service Unit according to values given during the experiment
4. Wait until the temperature of the cylinder not changing (until the system comes to steady-state)
5. Record voltage and current given to heater, temperature of the cylinder and temperature of the free stream.
6. Repeat the steps 3, 4 and 5 for three more sample data sets.
7. Turn on the centrifugal fan from the console.
8. Adjust the butterfly valve at the base of the setup to get a different stream velocity.
9. Wait until the temperature of the cylinder not changing (until the system comes to steady-state)
10. Record voltage and current given to heater, temperature of the cylinder and temperature and velocity of the stream.
11. Repeat the steps 8, 9 and 10 for three more sample data sets.

OBSERVATIONS

Sample	V	I	Ua	T1	T2
-	Volts	Amps	m/s	°C	°C
1					
2					
3					
4					
5					
6					
7					
8					

CALCULATED DATA

Sample	Q_{Input}	h_r	h_c	Q_r	Q_c	Q_{tot}
-	W	W/m^2K	W/m^2K	W	W	W
1						
2						
3						
4						
5						
6						
7						
8						

REPORT

In your report;

- Compare Q_{Input} and Q_{tot} for each sample and comment on the difference between them if there is any.
- Plot h_r and h_c with respect to cylinder temperature and comment on the effect of surface temperature on heat transfer mechanisms.
- Plot cylinder surface temperature and h_c with respect to air velocity at constant heat input and comment on the effect of air velocity on surface temperature and convective heat transfer.
- Discuss possible sources of discrepancies in the experiments if there is any.
- Mention the assumptions made during the experiment and discuss their effect on the results.