6.3 HT14C Laboratory Teaching Exercise A

Objective

To determine the combined heat transfer ($Q_{radiation}$ + $Q_{convection}$) from a horizontal cylinder in natural convection over a wide range of power inputs and corresponding surface temperatures.

To demonstrate the relationship between power input and surface temperature in free convection.

Method

By measuring the temperature on the surface of a horizontal cylinder subjected to heat loss by radiation and natural convection in combination then comparing the results obtained with those obtained from a theoretical analysis

Equipment Required

HT10XC Computer Compatible Heat Transfer Service Unit
HT14 Combined Convection and Radiation Accessory

Equipment set-up

Before proceeding with the exercise ensure that the equipment has been prepared as follows:-

Locate the HT14C Combined Convection and Radiation accessory alongside the HT10XC Heat Transfer Service Unit on a suitable bench.

Ensure that the horizontal cylinder is located at the top of the metal duct with the thermocouple located on the side of the cylinder (the cylinder can be rotated by releasing the thumb screw on the top of the mounting arrangement. Ensure that the thumb screw is securely tightened after adjustment).

Connect the thermocouple attached to the heated cylinder to socket T10 on the front of the service unit.

Connect the thermocouple located in the vertical duct to socket T9 on the service unit.

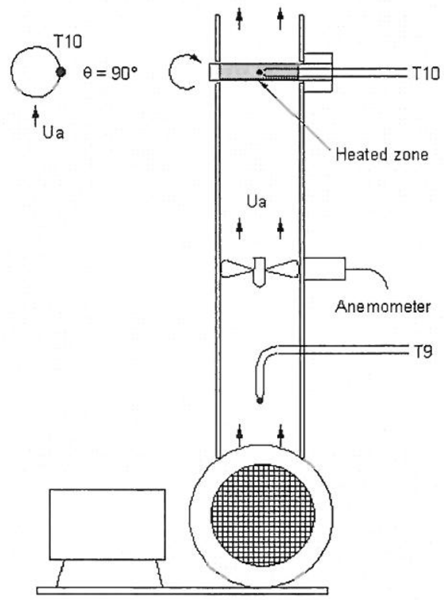
Set the manual/remote selector switch on the console to MANUAL.

Set the VOLTAGE CONTROL potentiometer to minimum (anticlockwise) and the selector switch to MANUAL then connect the power lead from the heated cylinder on HT14C to the socket marked Output 2 at the rear of the service unit.

Ensure that the service unit is connected to an electrical supply.

If using the HT14C software, check that the HT10XC console is connected to the PC via the USB socket, ensure that the manual/remote selector switch on the console is set to REMOTE, and run the HT14C software Exercise A.

If operating the accessory manually then leave the console selector switch set to MANUAL.



Theory/Background

If a surface, at a temperature above that of its surroundings, is located in stationary air at the same temperature as the surroundings then heat will be transferred from the surface to the air and surroundings. This transfer of heat will be a combination of natural convection to the air (air heated by contact with the surface becomes less dense and rises) and radiation to the surroundings. A horizontal cylinder is used in this exercise to provide a simple shape from which the heat transfer can be calculated.

Note: Heat loss due to conduction is minimised by the design of the equipment and measurements mid way along the heated section of the cylinder can be assumed to be unaffected by conduction at the ends of the cylinder. Heat loss by conduction would normally be included in the analysis of a real application.

In the case of natural (free) convection the Nusselt number Nu depends on the Grashof and Prandtl numbers and the heat transfer correlation can be expressed in the form:

Nu = f(Gr, Pr) and the Rayleigh number Ra = (Gr Pr)

The following theoretical analysis uses an empirical relationship for the heat transfer due to natural convection proposed by VT Morgan in the paper "The Overall Convective Heat Transfer from Smooth Circular Cylinders" published in TF Irvine and JP Hartnett (eds.), Advances in Heat Transfer vol. 16, Academic, New York, 1975, pp 199-269.

If T_s = Surface temperature of cylinder (K)
D = Diameter of cylinder (m)
L = Heated length of cylinder (m)
T_a = Ambient temperature of air (K)

Heat transfer area (surface area) $A_s = (\pi DL)$ (m2)

Heat loss due to natural convection $Q_c = H_{cm} A_s (T_s - T_a)$ (W)

Heat loss due to radiation $Q_r = H_{rm} A_s (T_s - T_a)$ (W)

Total heat loss from the cylinder $Q_{tot} = Q_c + Q_r$ (W)

The average heat transfer coefficient for radiation H_{rm} can be calculated using the following relationship:

$$Hr_m = \sigma \xi F \frac{(Ts^4 - Ta^4)}{(Ts - Ta)}$$ (Wm-2K-1)

where:

σ = Stefan Boltzmann constant σ = 56.7 x 10-9 (Wm-2K-4)
ξ = Emmisivity of surface (Dimensionless)
F = 1 = View factor (Dimensionless)

The average heat transfer coefficient for natural convection H_{cm} can be calculated using the following relationship:

$$T_{film} = \frac{(Ts + Ta)}{2}$$ (K)

$$\beta = \frac{1}{T_{film}}$$ (K-1)

$$Gr_D = \frac{g\beta(Ts - Ta)D^3}{\nu}$$

$Ra_D = (Gr_D\ Pr)$ therefore:

$$Ra_D = \frac{g\beta(Ts - Ta)D^3}{v}$$

$Num = c\ (Ra_D)n$ (From Morgan, where c and n are obtained from the table overleaf:)

$$Hc_m = \frac{(kNu_m)}{D}$$ (Wm-2K-1)

where:

Ra = Rayleigh number	(Dimensionless)
Gr = Grashof number	(Dimensionless)
Num = Nusselt number (average)	(Dimensionless)
Pr = Prandtl number	(Dimensionless)
g = Acceleration due to gravity = 9.81	(ms-2)
β = Volume expansion coefficient	(K-1
ν = Dynamic viscosity of air	(m2s-1)
k = Thermal conductivity of air	(Wm-1K-1)

Note: k, Pr, and ν are physical properties of the air taken at the film temperature T_{film}. (These may be obtained from the table in the HT14C Teaching Manual.)

The actual power supplied to the heated cylinder $Q_{in} = V\ I$ (W)

Table listing constant c and exponent n for natural convection on a horizontal cylinder (Source - Morgan):

RaD	c	n
10-9 to 10-2	0.675	0.058
10-2 to 102	1.02	0.148
102 to 104	0.850	0.188
104 to 107	0.480	0.250
107 to 1012	0.125	0.333

Alternatively a simplified equation may be used to calculate the heat transfer coefficient for free convection from the publication "Heat Transmission" WH McAdams, 3rd ed., McGraw-Hill, New York, 1959

$$Hc_m = 1.32\left(\frac{Ts - Ta}{D}\right)^{0.25}$$ (Wm-2K-1)

The value for H_{cm} should be calculated using both the original and simplified equations and the values compared.

Procedure

Refer to the Operation section (page 3-1) if you need details of the instrumentation and how to operate it.

Switch on the front Mains switch (if the panel meters do not illuminate check the RCD at the rear of the service unit, the switch should be up).

Set the Heater Voltage to 5 Volts. If using the software, adjust the voltage using the control box on the software screen. If operating the accessory manually, adjust the VOLTAGE CONTROL potentiometer to give a reading of 5 Volts on the top panel meter with the selector switch set to position V.

Allow the HT14C to stabilise. Monitor the temperature of the cylinder as indicated by thermocouple T10 using the software display, or using the lower selector switch/meter on the console.

When the temperatures are stable select the icon on the software menu bar to record the following:

T9, T10, V, I.

If not using the software, record these values manually using the console selector switches and displays.

Set the Heater Voltage to 8 Volts.

If using the software, select the icon to create a new results table.

Allow the HT14C to stabilise then repeat the above readings.

Set the Heater Voltage to 12 Volts.

Allow the HT14C to stabilise then repeat the above readings. Remember to create a new results sheet first if using the HT14C software.

Set the Heater Voltage to 15 Volts.

Allow the HT14C to stabilise then repeat the above readings.

Set the Heater Voltage to 20 Volts.

Allow the HT14C to stabilise then repeat the above readings.

Note: Do not set the heater voltage in excess of 20 Volts when operating the cylinder in natural convection (no forced airflow). The life of the heating element will be considerably reduced if operated at excessive temperature.

Results and Calculations

For this exercise the raw data is tabulated under the following headings:

Heater Voltage	V	Volts
Heater Current	I	Amps
Upstream air temperature	T9	(°C)
Surface temperature of cylinder	T10	(°C)

You should also estimate and record the experimental errors for these measurements.

For this exercise the following constants are applicable:

Diameter of cylinder	D = 0.01	(m)
Heated length of cylinder	L = 0.07	(m)
Emissivity of surface	$\xi = 0.95$	
Stefan Boltzmann constant	$\sigma = 56.7 \times 10\text{-}9$	(Wm-2k-4)

For each set of readings the derived results are tabulated under the following headings:

Heat flow (Power to heater)	Q_{in}	=	(Watts)
Heat transfer area (surface area)	A_s	=	(m2)
Heat transfer coefficient (natural convection)	H_{cm}	=	(Wm-2K-1)
Heat transfer coefficient (radiation)	H_{rm}	=	(Wm-2K-1)
Heat transferred by natural convection	Q_c	=	(W)
Heat transferred by radiation	Q_r	=	(W)
Total heat transferred	Q_{tot}	=	(W)

Estimate the cumulative influence of the experimental errors on your calculated values for A_s, H_{cm}, H_{rm}, Q_c, Q_r, Q_{tot} and Q_{in} and measured values for T9, T10, L and D.

Compare the theoretical values for Q_{tot} with the measured values for Q_{in} and explain any differences in values.

Compare the calculated heat transferred due to Convection Q_c and radiation Q_r

Compare the value for H_{cm} obtained using the simplified and full empirical equations and comment on any difference.

Plot a graph of surface temperature T10 against power input Q_{in} and observe the relationship.

Observe that the heat transferred from the cylinder to the surroundings increases with the difference between the surface temperature of the cylinder and the temperature of the surroundings.

Conclusions

You have demonstrated how heat transfer from a heated surface to its surroundings is a combination of heat loss due to natural convection and heat loss due to radiation (the effect of conduction must also be included where relevant) when the surface is located in stationary air.

For equilibrium, heat input to a surface must equal the heat transferred from the surface to its surroundings. Since heat transfer from a surface increases with difference in temperature between the surface and its surroundings, increased heat input to a surface results in an increase in the temperature of the surface.

The calculation of the heat transfer coefficient H_{cm} for natural convection involves the use of empirical equations which are specifically related to heat transfer from a horizontal cylinder. Empirical equations are available for other classical shapes which will allow a theoretical analysis to be performed.

The effect of moving air (forced convection) will be investigated in exercise HT14CC.

Note: Exercise HT14CB should be carried out on the completion of this exercise.

6.4 HT14C Laboratory Teaching Exercise B

Objective

To compare the contribution of heat transfer by convection with heat transfer by radiation and from the measurements to show the domination of the convective heat transfer coefficient H_c at low surface temperatures and the domination of the radiation heat transfer coefficient Hr at high surface temperatures

Method

By measuring the temperature on the surface of a horizontal cylinder subjected to heat loss by radiation and natural convection in combination then comparing the contribution by convection and radiation.

Note: If results are available from exercise HT14CA then this exercise can be completed using those results. Refer to the Theory section of this exercise followed by the Results and Calculations. The following instructions apply if results are not available:

Equipment Required

HT10XC Computer Compatible Heat Transfer Service Unit
HT14C Combined Convection and Radiation Accessory

Equipment set-up

Before proceeding with the exercise ensure that the equipment has been prepared as follows:-

Locate the HT14C Combined Convection and Radiation accessory alongside the HT10XC Heat Transfer Service Unit on a suitable bench.

Ensure that the horizontal cylinder is located at the top of the metal duct with the thermocouple located on the side of the cylinder. (The cylinder can be rotated by releasing the thumb screw on the top of the mounting arrangement. Ensure that the thumb screw is securely tightened after adjustment.)

Connect the thermocouple attached to the heated cylinder to socket T10 on the front of the service unit.

Connect the thermocouple located in the vertical duct to socket T9 on the service unit.

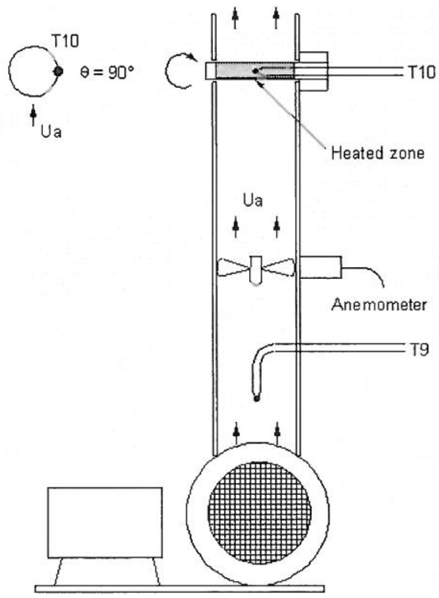
Set the manual/remote selector switch on the console to MANUAL.

Set the VOLTAGE CONTROL potentiometer to minimum (anticlockwise) and the selector switch to MANUAL then connect the power lead from the heated cylinder on HT14C to the socket marked Output 2 at the rear of the service unit.

Ensure that the service unit is connected to an electrical supply.

If using the HT14C software, check that the HT10XC console is connected to the PC via the USB socket, ensure that the manual/remote selector switch on the console is set to REMOTE, and run the HT14C software Exercise B.

If operating the accessory manually then leave the console selector switch set to MANUAL.



Ensure that the service unit is connected to an electrical supply.

Theory/Background

When a horizontal cylinder, with its surface at a temperature above that of its surroundings, is located in stationary air then heat loss from the cylinder will be a combination of natural convection to the air (air surrounding the cylinder becomes less dense and rises when it is heated) and radiation to the surroundings.

Note: Heat loss due to conduction is minimised by the design of the equipment and measurements mid way along the heated section of the cylinder can be assumed to be unaffected by conduction at the ends of the cylinder. Heat loss by conduction would normally be included in the analysis of a real application.

The following theoretical analysis uses an empirical relationship for the heat transfer due to natural convection proposed by WH McAdams in the publication "Heat Transmission", third edition, McGraw-Hill, New York, 1959.

Total heat loss from the cylinder	$Q_{tot} = Q_c + Q_r$ where:
Heat loss due to natural convection	$Q_c = H_c A_s (T_s - T_a)$ and
Heat loss due to radiation	$Q_r = H_r A_s (T_s - T_a)$
Heat transfer area (surface area)	$A_s = (\pi d L)$

The heat transfer coefficients H_{cm} and H_{rm} can be calculated using the following relationships:

$$HC_m = 1.32\frac{(Ts - Ta)^{0.25}}{d}$$

(simplified empirical equation from McAdams)

$$Hr_m = \sigma\xi F\frac{(Ts^4 - Ta^4)}{(Ts - Ta)}$$

where:

σ = Stefan Boltzmann constant (σ = 56.7 x 10-9 Wm-2k-4)
ξ = Emmisivity of surface
T_s = Surface temperature of cylinder (K)
T_a = Ambient temperature (K)

Actual power supplied to the heated cylinder $Q_{in} = V I$ (Watts)

Procedure

Refer to the Operation section (page 3-1) if you need details of the instrumentation and how to operate it.

Switch on the front Mains switch (if the panel meters do not illuminate check the RCD at the rear of the service unit, the switch should be up).

Set the Heater Voltage to 5 Volts. If using the HT14C software, adjust the heater setting using the control box on the mimic diagram screen. If operating the accessory manually using the console then set the heater voltage by adjusting the VOLTAGE CONTROL potentiometer to give a reading of 5 Volts on the top panel meter with the selector switch set to position V.

Allow the HT14C to stabilise. If using the software then monitor the surface temperature of the cylinder T10 on the mimic diagram screen. If operating the accessory manually then monitor T10 using the lower selector switch/meter on the console.

When the temperatures are stable select the icon on the top software toolbar to record the following:

T9, T10, V, I.

If operating the accessory manually then record these values from the two console displays using the display selector knobs to select each required value.

Set the Heater Voltage to 8 Volts.

Allow the HT14C to stabilise then repeat the above readings.

Set the Heater Voltage to 12 Volts.

Allow the HT14C to stabilise then repeat the above readings.

Set the Heater Voltage to 15 Volts.

Allow the HT14C to stabilise then repeat the above readings.

Set the Heater Voltage to 20 Volts.

Allow the HT14C to stabilise then repeat the above readings.

Note: Do not set the heater voltage in excess of 20 Volts when operating the cylinder in natural convection (no forced airflow). The life of the heating element will be considerably reduced if operated at excessive temperature.

Results and Calculations

For this exercise the raw data is tabulated under the following headings:

Heater Voltage	V	Volts
Heater Current	I	Amps
Upstream air temperature	T9	(°C)
Surface temperature of cylinder	T10	(°C)

You should also estimate and record the experimental errors for these measurements.

For this exercise the following constants are applicable:

Diameter of cylinder	d = 0.01	(m)
Heated length of cylinder	L = 0.07	(m)

For each set of readings the derived results are tabulated under the following headings:

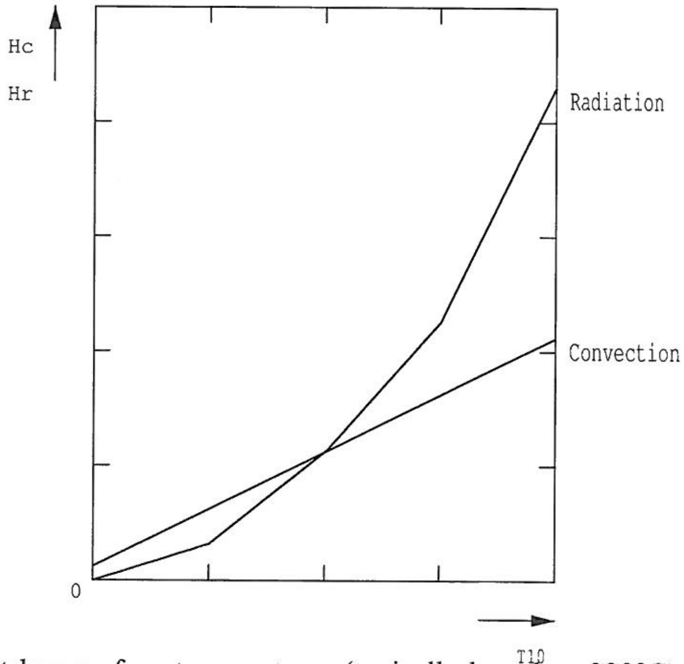
Heat flow (Power to heater) Q_{in} = (Watts)

Heat transfer area (surface area)	A_s	=	(m2)
Heat transfer coefficient (natural convection)	H_{cm}	=	(Wm-2K-1)
Heat transfer coefficient (radiation)	H_{rm}	=	(Wm-2K-1)
Heat transferred by natural convection	Q_c	=	(W)
Heat transferred by radiation	Q_r	=	(W)
Total heat transferred	Q_{tot}	=	(W)

Estimate the cumulative influence of the experimental errors on your calculated values for A_s, H_{cm}, H_{rm}, Q_c, Q_r, Q_{tot} and Q_{in} and measured values for T9, T10, L and D.

Compare the calculated heat transfer due to convection Q_c with the calculated heat transfer due to radiation Q_r by plotting graphs of H_{cm} and H_{rm} against the temperature of the surface T_s (= T10 +273).

Your graph should be similar to the diagram below:



Observe that at low surface temperatures (typically less than 230°C) the heat transfer coefficient H_{cm} due to natural convection is greater than the heat transfer coefficient H_{rm} due to radiation. Conversely, at high surface temperatures (typically greater than 230°C) the heat transfer coefficient H_{cm} due to natural convection is less than the heat transfer coefficient H_{rm} due to radiation and as the temperatures exceeds 400°C the effect of radiation becomes dominant.

Conclusions

You have demonstrated how the contribution of natural convection and radiation towards the heat loss from a hot surface varies with the temperature difference between the hot surface and the ambient air/surroundings (the effect of conduction must also be included where relevant). Convection is more dominant when the temperature difference is small. Radiation is more dominant when the temperature difference is large.

The effect of moving air (forced convection) will be investigated in exercise HT14CC.

Note: Exercise HT14CC should be carried out on the completion of this exercise.