

ENSC 388: Engineering Thermodynamics and Heat Transfer

Experiment 3: Free and Forced Convection

Objective

Determination of heat transfer coefficient for free and forced convection for different geometries.

Apparatus

Figure 1 shows the experimental instrument in details. This unit has the following parts:

- The air duct (1) with a cross-section of $120 \times 120 \text{ mm}^2$ and a length of 1 m is used to guide the flow.
- The air channel has several measuring glands (2) that enable one to record the temperature at various points by using a type *K* thermocouple (3). In addition, a flow sensor (4) measures the volumetric flow rate of the inlet air, and two PTC elements (5, 6) record the inlet and outlet temperatures.
- Heater inserts (7-9) are used in the duct. These are mounted using simple toggle type fasteners. The different heated surfaces (flat plate, pipe bundle or fins) are each heated by four resistive heaters with a maximum total power output of approximate 170W . The voltage applied is adjustable giving a variable heat output. Bi-metallic strips, which interrupt the supply of power when a set threshold is reached, are used to ensure that the temperature does not exceed 120°C .
- The control and display unit (10) contains the power supply and the regulators for the fan and heater inserts. In addition, this unit displays the electrical power supplied to the heater elements, the volumetric flow rate, the inlet and outlet air temperature and the temperatures measured with the thermocouple. A PC can be connected at the rear for data acquisition.

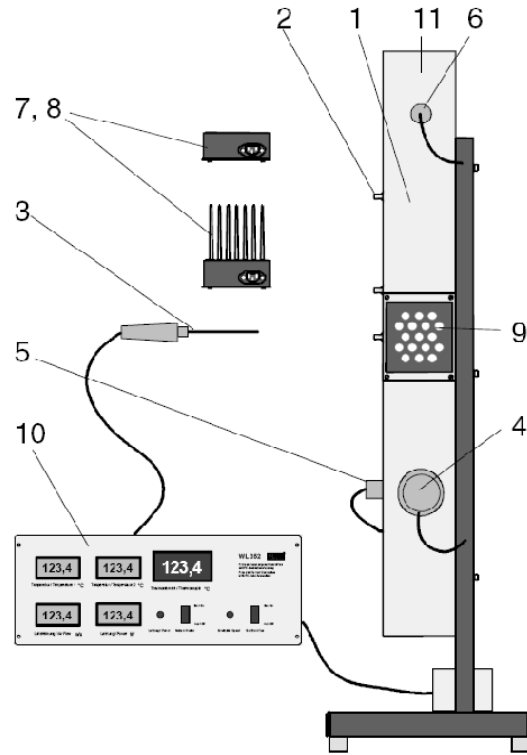


Figure 1- Components of experimental apparatus

Software

The LabView software is used to display the measured data. The program has 6 screens that are arranged hierarchically. Figure 2 shows the system diagram containing the current measured values; this is displayed after starting the program. Left clicking on the relevant buttons (8) takes you to the other screens:

- Time elapsed (1);
- Curve plotting (2);
- Initialization (3);
- About GUNT (4);
- Exit the program (5).

You can switch between the screens at any time. The right-hand area of the screen shows the calculated figures for the mass flow rate (1), the amount of heat transferred (2), the efficiency (3), the coefficient of heat transfer (4) and the Reynolds (5) and Nusselt numbers (6).

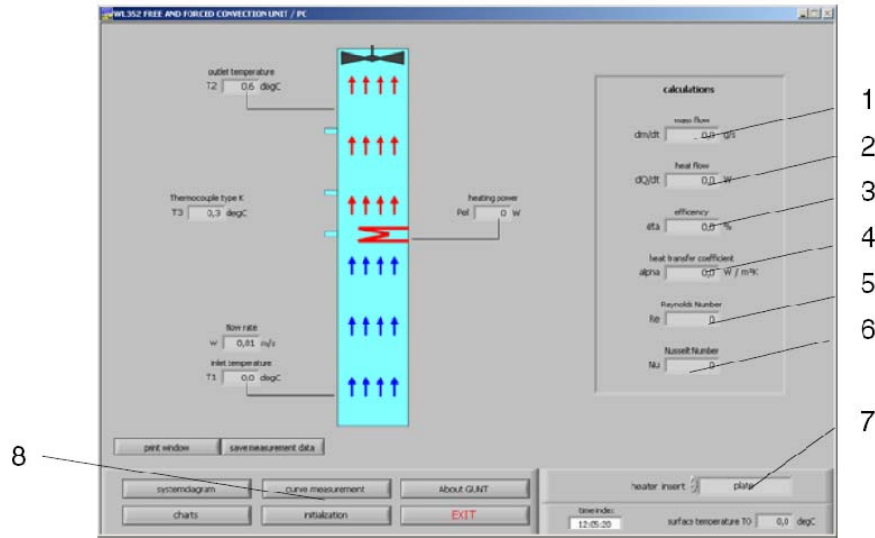


Figure 2- System Diagram

Selecting the heater insert used (7) is a prerequisite for correct calculation. The other information necessary to perform the calculation such as: ambient temperature, air pressure and relative humidity, is entered in the “Initialization” screen.

The system diagram shows the schematic layout of the system with the measuring points and the associated current measured values. The buttons (8) take you to the other windows.

To obtain correct calculations, it is necessary to determine and save the heater temperature. Therefore, the uninstalled plate heater is operated at the desired power. The thermocouple is used to measure the surface temperature T_0 (directly on the surface for uninstalled plate and using measuring connections for pipe bundle and disks). Once a stationary value is established, it is saved by pressing the button (8). These values are used as a basis for subsequent calculations and are overwritten each time the button (8) is pressed. The plate heater can then be installed in the channel and the experiments can be commenced. The ambient temperature, the air pressure and the relative humidity must also be entered manually in the initialization screen shown in Fig. 3.

Time elapsed screen is shown in Fig. 4. All measured values of the temperatures T_1 , T_2 , and T_3 , the averaged velocity w and the power P_e are continuously recorded over time and are displayed graphically. This allows the process and the establishment of a steady-state condition to be monitored very clearly. Consider the following notes regarding Fig. 4:

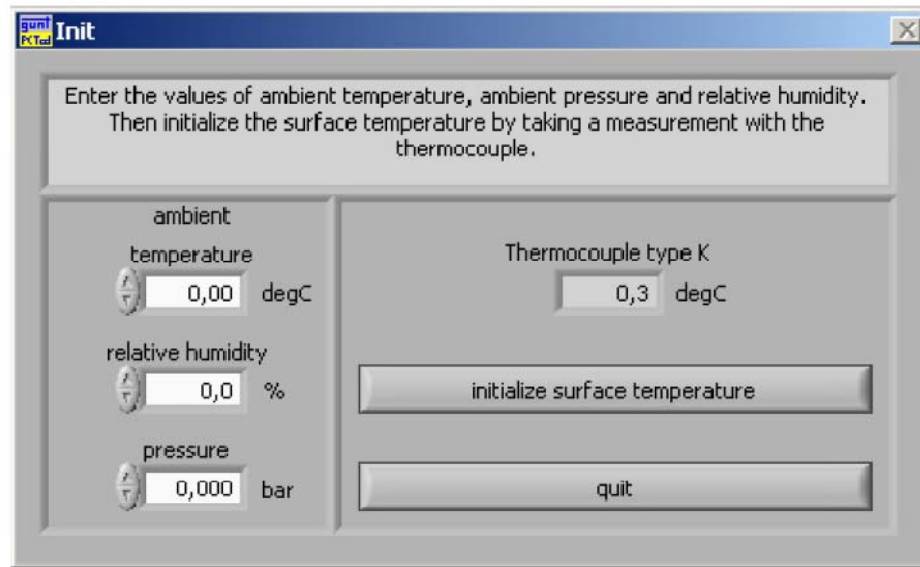


Figure 3- Initialization screen

1. This field can be used to set the feed speed for the plotter;
2. Allows a background color to be selected (left click);
3. Prints the graph as a screenshot on the default printer.
4. Deletes the current graph.
5. Allows changes to be made to the characteristic curve displays (left click).
6. This button can be used to stop the time elapsed.
7. Left clicking on the initial or final values allows the axis scaling to be changed.
8. Allows you to switch to the other screens.
9. The heater insert used must be specified here.
10. Displays the heater insert surface temperature measured in the initialization screen.

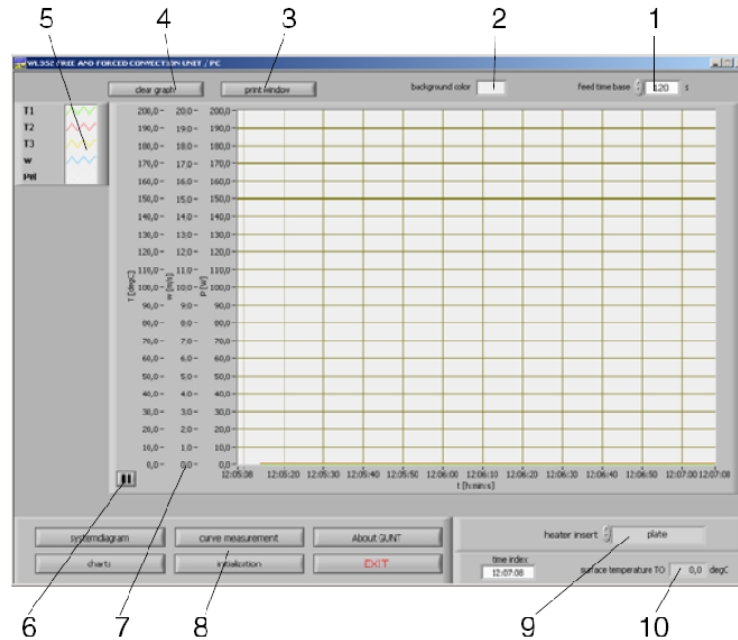


Figure 4- Time elapsed screen

The curve plotting window is shown in Fig. 5. This screen allows one to depict measuring curves directly. The variables to be displayed can be assigned to the x -axis (only 1 variable) and y -axis (up to 4 variables). The following numbers shown on Fig 5 can be used in preparing the required graphs.

1. Allows a background colour to be selected.
2. Prints the graph as a screenshot on the default printer.
3. The recorded variables are assigned to the x and y axis for display here.
4. Prints the measured values on the default printer.
5. Prints just the x/y graphs of the measured values.
6. Allows changes to be made to the characteristic curve Displays.
7. With more than 1 curve, allows selection of the curve to be edited
8. Comments field - Shows the comments entered when opening a new curve.
9. Allows you to switch to the other screens.
10. Button for selecting a measuring point for measured data already recorded (for editing)
11. Displays the heater insert surface temperature measured in the initialization screen.
12. Button for creating a new curve
13. Button for deleting a measuring point
14. Button for plotting a new measuring point

- 15. Button for saving a plotted curve
- 16. Button for loading a saved curve
- 17. Button for deleting a curve from the RAM memory

All values are saved, i.e. measured values and calculated values.

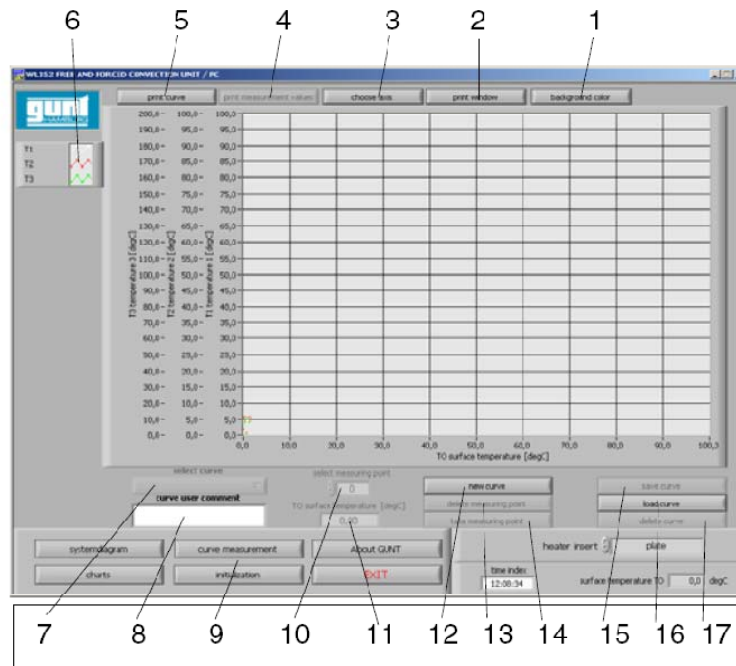


Figure 5- Curve plotting screen

Theory

There are three modes for heat transfer: convection, conduction, and radiation. The Convection heat transfer plays an important role in many industrial applications. Based on different criteria, convection can be divided in to different categories from different aspects. In the most general division, it is subdivided into free and forced convection. In the forced convection, the fluid to be heated is blown or pumped past the heated surface by employing a pump or a fan, while in the natural (or free) convection, fluid flow is naturally achieved based on the density variation in the heated fluid.

The heat transfer rate to the fluid, \dot{Q} , can be calculated using the first law of thermodynamics for the heated fluid:

$$\dot{Q} = \dot{m} \Delta h \quad (1)$$

where Δh is the enthalpy variation of the fluid in the duct and \dot{m} is the mass flow rate which is calculated as:

$$\dot{m} = \rho w A \quad (2)$$

here ρ is the air density, w is the averaged velocity and A is cross-sectional area of the duct which is equal to $0.0144m^2$ in this experiment. The air density can be found from thermodynamics tables. Using perfect gas assumption for the air, Eq. (1) becomes:

$$\dot{Q} = \dot{m} C_p \Delta T \quad (3)$$

The temperature difference ΔT is calculated from the difference between the average inlet and outlet temperatures. The specific heat capacity of the air C_p is also dependant on the air temperature and should be found from thermodynamics tables. Since the temperature is varying in the duct length, the value of C_p should be evaluated in the averaged temperature of air in the duct, T_M :

$$T_M = \frac{T_{in} + T_{out}}{2} \quad (4)$$

The heat sources on the test stand consist of electrical resistors; thus, the amount of power that is consumed by the heaters, P_e , can be considered as a measure of the amount of heat released.

The factor for efficiency η provides information on the losses which occur during heat transfer. This factor indicates the portion of the input energy that is transferred to the fluid. This can be written as follows:

$$\eta = \frac{\dot{Q}}{P_e} \quad (5)$$

The efficiency shows all losses which result from convection and radiation to the surroundings and not to the fluid. The transfer of heat from a surface to a fluid can be described mathematically as follows:

$$\dot{Q} = A \alpha T_m \quad (6)$$

where α is the heat transfer coefficient and T_m is an average temperature. The heat transfer rate is the same as the amount calculated from Eq. (3). Determination of T_m is challenging. If one assumes that temperature is varying linearly along the duct, T_m will be identical to T_M calculated from Eq. (4). Another important value introduced in the literature is Log Mean Temperature (LMT). It is calculated using the following formula:

$$T_m = \frac{(T_{0in} - T_{Lin}) - (T_{0out} - T_{Lout})}{\ln \frac{(T_{0in} - T_{Lin})}{(T_{0out} - T_{Lout})}} \quad (7)$$

Since the surface temperature T_0 of the heater remains almost constant across the entire area and only the temperature of the air T_L changes significantly between the inlet and the outlet, one can simplify this equation:

$$T_m = \frac{(T_{Lout} - T_{Lin})}{\ln \frac{(T_{0in} - T_{Lin})}{(T_{0out} - T_{Lout})}} \quad (8)$$

Therefore, the heat transfer coefficient, α , can be evaluated from Eqns. (3), (6), and (8). The heat transfer depends not only on the temperature difference and the surface material of the heater, but is also influenced by the flow regime, i.e., laminar or turbulent flow. Reynolds number is a criterion for defining whether a flow is turbulent or laminar. For a flow over a flat plate the transition between these two regimes occurs at approximately $Re_{crit.} = 1 - 5 \times 10^5$. However, there are other values for pipes and fins. The Reynolds number is defined as:

$$Re = \frac{w l}{\nu} \quad (9)$$

where l is characteristic length scale which is the plate length for flat surfaces and ν is the kinematic viscosity of the fluid. The kinematic viscosity of the air ν is temperature dependant and can be taken from thermodynamics tables at T_M . The Nusselt number is dimensionless and is used in measuring heat transfer rates:

$$Nu = \frac{\alpha l}{k} \quad (10)$$

where k is thermal conductivity. The Nusselt number can be calculated once the heat transfer coefficient, α , is known. The following equation offers a further way of determining the Nusselt number for a parallel flow over a smooth surface (plate) approximating to a laminar flow:

$$Nu = 0.664 Re^{0.5} Pr^{0.33} \quad (11)$$

Using the values obtained from Eq. (11) it is possible to check the accuracy of experiments for flat plate heater.

Procedure

At the beginning of the experiment the heater element with the flat plate is connected to the control and display unit prior to being fixed in the air duct. Once the power supply has been connected, the potentiometer on the control unit is set to 100% and the surface temperature T_0 is measured using the thermocouple. Once a steady state condition has been reached, there is no noticeable temperature change at the surface of the heater element, the temperature is saved. The heater is then placed in the duct. Once again it is necessary to wait until a steady state condition is reached. The following values are measured for evaluation:

- Temperature T_{in} at the inlet to the air duct;
- Volumetric flow rate at the inlet to the air duct;
- Temperature T_{out} at the outlet of the air duct.

This experimental sequence is applicable to all the subsequent experiments, see Table 1. In the case of the pipe bundle and the heater with fins, the surface temperature can be measured prior to fitting in the air duct using the measuring glands.

Turn on the fan and repeat the abovementioned sequence. Increase the fan power to 100% of its rated capacity with the heater at full power.

The temperature drop within the heated pipe bundle is measured on the heater insert for the free and forced convection cases. The heater insert is operated at 100% power output and the thermocouple pushed into the air duct through the measuring gland such that the tip is in the centre of the cylinder bore. The thermocouple is then removed from the first measuring gland and is inserted in the other three holes in the cylinder.

Table 1: Measured data sheet.

	Flat Plate		Pipe bundle		Fins	
	natural	forced	natural	forced	natural	forced
T_{in}						
T_{out}						
w (m/s)						
P_{el}						
η						

After completing the measurements, find the efficiency of the system for each heater and the convection mode. Determine effects of flow regime on the heat transfer rate. For the flat plate heater

calculate the accuracy of the experimental data with comparison of the measured values to the one obtained from Eq. (11).

Discussion

- 1) What are the differences between laminar and turbulent flows? Which one has the higher heat transfer coefficient?
- 2) What is the difference in the measured values of heat transfer coefficient if one uses linear average temperature instead of LMT?