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CBE 140A: Heat Convection

1 Introduction

Relevant applications of convective heat transfer can be found in a myriad of unit operations: shell-and-tube heat exchangers, air-cooled heat exchangers, solids-heating rotating drums, air conditioning, boilers and condensers, cryogenic processes, evaporative cooling towers, and more. Predicting and characterizing the behavior of these types of systems requires an understanding of the fundamentals of convective heat transfer, which is introduced in this experiment.

2 Objective

This apparatus will make use of electrically heated metal plates of varying geometries, to be cooled in air in a rectangular duct. The impact of heating power supplied, plate geometry, and air speed on the temperature profile in the plate's extended surface and the effectiveness of heat transfer will be explored.

3 Theory

The rate of heat transfer from a solid to a fluid (in this case, from a metal plate to air) can be predicted using Newton's law of cooling:

$$Q = hA(T_{\text{surface}} - T_{\text{fluid}}) \tag{1}$$

$$\begin{aligned} \text{where } Q &= \text{heat transfer in units of energy per time,} \\ h &= \text{convective heat transfer coefficient, and} \\ T &= \text{temperature,} \end{aligned}$$

Where the subscripts denote the location at which a variable is assessed.

Empirical studies have been able to predict convective heat transfer coefficients with reasonable accuracy using dimensionless analysis. Many correlations exist, depending on the geometry, flow type, surface conditions, etc., and are well documented in the corresponding textbooks. For example, fully-developed laminar flow over a constant-temperature plate yields the following (derived in [1, 352]), relating the Nusselt number (which, once known, allows determination of the convective heat transfer coefficient, h) to a function of the Prandtl and Reynolds numbers:

$$Nu = 0.664 Pr^{\frac{1}{3}} \sqrt{Re} \tag{2}$$

From these types of correlations, the convective heat transfer coefficient can be estimated. Note that the appropriate correlation should be employed based on the geometry and type of flow and, even then, these empirical correlations can be expected to have ±15% accuracy.

With the estimation of h, it is not immediately clear we can calculate the rate of heat transfer. In particular, for the cooling of an extended surface, we should not expect the surface temperature of the plate to be uniform. Instead, it is likely there will be a drop in temperature as the distance from the heated wall increases. To account for this, heat transfer textbooks often provide substantial detail for how to develop an analytical model for temperature as a function of position within a fin. This process involves development of a one-dimensional ordinary differential equation which can be solved with boundary conditions of varying levels of accuracy, but resulting in equations of varying complexity. For example, [2, 384] describes how, assuming a rectangular fin has a known constant temperature where it connects to the wall and has an effectively insulated tip, one can arrive at the following:

$$\frac{T(x) - T_{\text{air}}}{T_{\text{wall}} - T_{\text{air}}} = \cosh\left(\sqrt{\frac{hL^2}{kB}}\frac{x}{L}\right) - \tanh\left(\sqrt{\frac{hL^2}{kB}}\right)\sinh\left(\sqrt{\frac{hL^2}{kB}}\frac{x}{L}\right) \tag{3}$$

where L = fin length,
k = thermal conductivity of the fin material, and
B = half the fin thickness.

Another approach to estimating the total heat transfer through a fin is to introduce an effectiveness factor, η, which is defined as the ratio of actual heat transferred to the maximum heat transferred (easily determined by assuming the entirety of the fin surface were at the wall temperature). For the analytical solution above, η can be calculated directly:

$$\eta = \frac{Q}{Q_{\text{max}}} = \frac{\tanh\left(\sqrt{\frac{hL^2}{kB}}\right)}{\sqrt{\frac{hL^2}{kB}}} \tag{4}$$

For other geometries, η might be more easily determined using empirically-determined correlations or charts, such as Figure 15.12 in [1].

4 Experimental Apparatus

Figure 1 illustrates the heat convection apparatus. A control console, which can be powered on using the switch (1), provides variable electrical power to the plates, either a flat surface (9), a finned plate (11), or a pinned plate (12). All plates are easily secured in the rectangular air duct at (9) through an opening on its back, visible behind an acrylic plate on the front. Power supplied can be controlled with the knob (6) and is displayed on the box (3) and on a Kill-a-Watt meter (4). (Wiring is not shown for simplicity.) The control console also can manipulate the air speed with the knob (5), which controls the fan (8), pulling air up the duct from its lower opening (7). Air velocity can be recorded through use of a Vernier anemometer, which automatically logs data on a connected computer. Temperature can be observed through a probe which connects to the control box, displayed at (2). The surface temperatures across the extended surfaces can be recorded on a computer using bluetooth-enabled Vernier temperature sensors (not shown), which can be inserted into the duct through ports (10) at different distances from the plate.

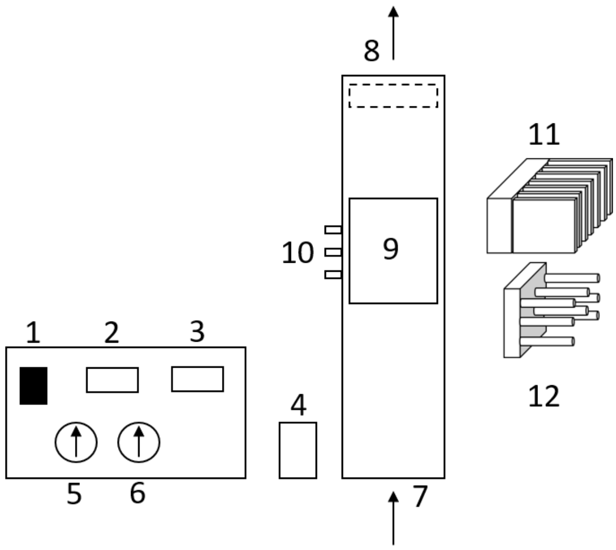

Figure 1: Experiment 7: heat convection apparatus.

5 Safety

The major hazards associated with this experiment are the following: The control console, powered from an electrical outlet, introduces the risk of injury from electric shock. Avoid by ensuring the power cord is not touched when in operation. The fan moving parts introduce risk of injury if anything is caught by it. Mitigate this risk by ensuring any long hair is securely tied back. This list is only a starting point and not intended to be fully comprehensive—please keep the safety of yourself and others in mind throughout the laboratory sessions.

6 Experimental Procedure

Insert the finned plate into the air duct and secure it. Set the heater power to 20 watts. Manipulate the fan speed until an anemometer observes the air velocity to be 1.0 meters per second. Begin recording the temperatures of the fin at multiple locations as the system heats up. Simultaneously, periodically record the plate base temperature as displayed on the control console. Note the temperature sensor positions so the distances from the fin base can be recorded later. Record the ambient air temperature (T_a). Once steady state is reached, record the ambient air inlet and outlet temperatures and velocities.

Conduct additional trials investigating the effects of: plate geometry (flat, finned, and pinned), air velocity (free convection, as opposed to forced convection, can be studied with the fan off), and heat power supplied (setting the power to zero allows study of cooling time).

Notes: The time to reach steady state might be shortened if the system is throttled by increasing heating power beyond the set point until the expected steady state temperature is reached and subsequently reducing the power back to the set point. Do not throttle the system for all trials, as the transient behavior of the system will also be studied. The control console has an automatic shut-off feature if the system overheats. It will restore control to the user once it sufficiently cools to a safe temperature.

7 Data Analysis

For each trial, characterize the convective heat transfer process by: plotting the difference between system and ambient temperatures ($T - T_a$) as a function of time and position (if applicable); calculating experimental values of h, Q, and η. Compare these charts and values to their expected shapes and values—if there is disagreement, what might be the cause, and is there evidence for it? Perform a mass and energy balance for the air at steady state: are mass and energy conserved? If not, what might be the cause, and is there evidence for it?

Based on the trials you were able to complete, investigate the effect of plate geometry, air velocity, and heat power on h, Q, and η. Note this is combinatorial, allowing up to nine methods of analysis. Comment on significant results. Do they agree with the predicted relationships between these parameters? If not, what might be the cause, and is there evidence for it? Is there an optimal combination of settings for a maximum rate of heat transfer?

References

[1] Julian Smith, Warren McCabe, and Peter Harriott. *Unit operations of chemical engineering.* McGraw-Hill, seventh edition, October 2005.

[2] Stanley Middleman. *An introduction to mass and heat transfer.* John Wiley and Sons, Inc., 09 1998.