AN EXPERIMENT SUBJECTING A CYLINDRICAL COOLING FIN TO FORCED AIR CONVECTION

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Abstract *? This paper describes the fabrication, operation, and analysis of an experiment in which a cooling fin is subjected to forced air convection. The fin is a cylindrical metal rod attached to a flat plate. This assembly is placed on a heating unit. A fan is used to subject the heated fin to forced air convection. The flat plate and lower portion of the rod are insulated to minimize losses to the environment from areas other than the cylindrical fin. The temperature towards the base of the fin is monitored to establish the fin base temperature and the presence of a steady state. Once steady state has occurred the on and off cycling of the heating unit is observed to determine the power input to the fin. The air speed and temperature, along with the fin geometry, material and base temperature are used to predict the heat loss through the fin. The predicted heat loss is then compared to the determined power input.*

INTRODUCTION

The author instructs a heat power class for mechanical engineering technology students. The class covers the topics of thermodynamics and heat transfer. The experiment described in this paper was developed for use in this course to help students understand and appreciate some of the parameters and calculations involved in determining heat transfer due to forced convection. What appears to be a simple experiment actually requires numerous steps with multiple properties and equations whose meaning can be better understood by application.

APPARATUS

The fin assembly consists of a metal rod attached to a metal plate and is shown in Figure 1. The rod material is 6061-T6 aluminum that is one inch in diameter and eight inches long and flat on both ends. The plate is one quarter inch thick aluminum and six by six inches square. The fin was attached to the plate from below using a machine screw. The lower portion of the rod was tapped to accept the screw. A recessed area and through hole in the bottom of the plate allow the screw to attach to the rod with no protrusion from the bottom surface of the plate. This allowed the fin assembly to sit flat on the heating unit. Five equally spaced thermocouples were recessed along the length of one side of the cylindrical fin to facilitate temperature measurement.

A 1/3 horsepower motor driving a squirrel cage fan was used to supply air current to the fin. The airflow was routed through an air duct. The exit portion of the duct can be seen in the upper left hand corner of Figure 2. Care was taken during setup to provide a uniform wind profile across the length of the exposed portion of the fin assembly. A thermo anemometer was used to determine the wind velocity magnitude and profile near the front of the fin. An average velocity was used for calculations.

The duct exit height was approximately equal to one half the height of the rod. For this and other reasons it was desirable to only have the upper half of the rod exposed to the airflow. The bottom half of the fin assembly was insulated with a wire mesh basket loosely stuffed with mineral wool to minimize heat losses from other than the upper half of the fin surface. This is shown in Figure 2.

The heating unit was a hot plate rated at 750 watts and operated with 115 VAC. The hot plate had a power light that indicated when the heating element is activated and a rotary knob for temperature control of the platen and is shown in Figure 2. The heating element cycled on and off to maintain the desired platen temperature.

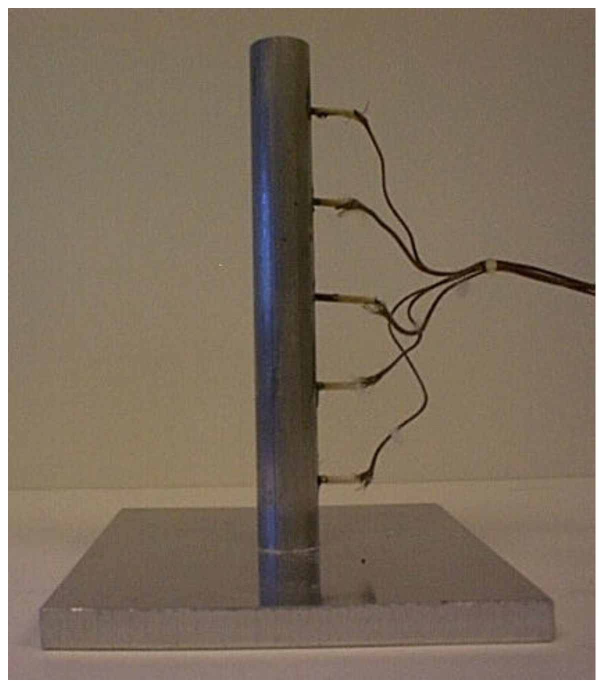

FIGURE. 1
FIN APPARATUS CONSISTING OF ROD, BASE, AND THERMOCOUPLES

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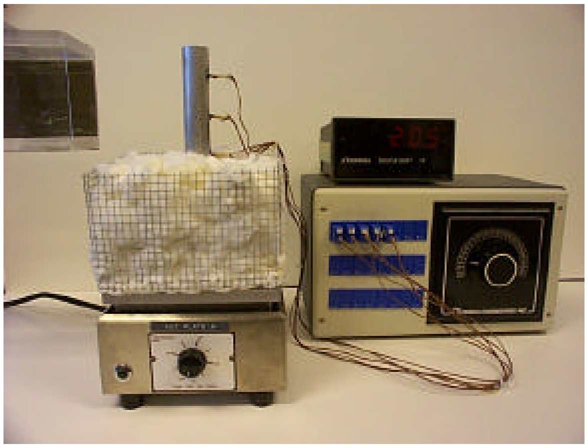

FIGURE. 2
DUCT EXIT, INSULATED FIN ON HOT PLATE, AND TEMPERATURE METER

The power input to the hot plate was determined by timing a sequence of on and off cycles of the power indicator light. This was done using a stopwatch after the fin assembly had reached equilibrium. The duration of each of ten on cycles and ten off cycles was measured and recorded to determine the percentage of time that the heating element was active at steady state. The cycles were not consistent in length so a number of cycles were used to obtain an average on time percentage.

The hot plate was plugged into a wattmeter to obtain an accurate value for the power being supplied by the heating element. Although the hot plate was rated at 750 watts, the wattmeter indicated that once the unit was at steady state only 650 watts of electricity were being supplied to the heating element during on cycles. No electrical wattage was supplied to the heating element during off cycles.

PROCEDURE

The first step was to determine the heat losses around the heating unit base plate. The wire basket is placed on the heating unit without the fin assembly installed. The basket is stuffed with mineral wool and the temperature knob was adjusted to the desired temperature setting. The higher the setting, the more heat transfer, but greater care was required to prevent personal injury due to someone or something making contact with a hot surface. After the unit has cycled off and on a few times a sequence of ten on and ten off cycles are measured and recorded. It usually took about fifteen minutes to reach thermal equilibrium. Having one student measure on times and another student measuring off times helped insure that the times were recorded accurately. The insulation and basket was then removed as a unit and the hot plate was turned off.

Students then measured the fin geometry, material, and thermocouple locations. The fin assembly was then placed on the hot plate and the wire basket and insulation were installed. Care was taken since the heating unit was still very hot. The platen temperature knob is then adjusted to the same temperature setting as was previously used and the unit was allowed to heat until the heater element power cycled off. It usually took about thirty minutes to reach thermal equilibrium. The blower was then turned on and the thermocouple temperatures were monitored until the temperatures stabilize. Thermocouple temperatures were then recorded as well as wind speed and room temperature. A thermo anemometer was used to determine the wind velocity magnitude and profile near the front of the fin. An average velocity was used for calculations. A stopwatch was used to measure a sequence of ten on and ten off cycles of the heating element. After all data was recorded the power to the hot plate and blower was turned off.

ANALYSIS

Background

Newton's law of heating and cooling (1) was used to estimate the heat transfer *Q*, due to convection.

$$Q = h\,A\,(T_{base} - T_{air}) \tag{1}$$

The temperature of the fluid stream, T_{air}, was measured using a thermometer. The base temperature of the fin, T_{base},, for our experiment was considered to be the temperature of the fin at the top of the insulation. A number of steps were required to determine the heat transfer coefficient *h*. The exposed surface area of the fin *A*, was calculated using (2) and the diameter of the rod, *D*, and the exposed length, *L*, of the fin.

$$A = ?\ D\,(L + D/4) \tag{2}$$

Equation (1) assumes a 100% efficient fin in which the entire exposed portion of the fin is at T_{base}. The temperature data gathered in the experiment showed that this was not the case so a fin efficiency factor, $?_{fin}$, was used to modify (1) as follows:

$$Q = ?_{fin}\,h\,A\,(T_{base} - T_{air}) \tag{3}$$

$?_{fin}$ was equal to the actual heat transfer rate from the fin divided by the ideal heat transfer rate from the fin.

The text used for the course [1] provided a figure [2] that enabled the determination of an estimation of the fin efficiency factor using fin dimensions and geometry, thermal conductivity of the fin material, k_{solid}, and *h*.

The text also provided a table [3] that was obtained from empirical data and that facilitated the determination of the Nusselt number, *Nu*, in terms of the Reynolds number, *Re*, and the Prandtl number, *Pr*, for flow across a fin using the fin cross sectional geometry and *Re*. *Nu* is a dimensionless convection heat transfer coefficient that represents the enhancement of heat transfer through a fluid layer as a result of convection relative to conduction across the same fluid layer. *Pr* is a dimensionless quantity equal to the ratio of the fluid tendency to dissipate momentum to the fluid tendency to dissipate heat. *Re* is a dimensionless quantity equal to the ratio of the fluid inertia forces to the fluid viscous forces [1]. The air velocity, $V_?$, and kinematic viscosity, ?, and *D* are used to find *Re*. *Re* is between 4,000 and 40,000 for our experiment. Using a table [3] in the text we found:

$$Nu = 0.193\ Re^{0.618}\ Pr^{0.333} \qquad (4)$$

where:

$$Re = V_?\ D\,/\,? \qquad (5)$$

Finally, *h* was be determined using *Nu*, *D*, and the thermal conductivity of air, $k_{air,}$ in (6):

$$h = k_{air}\ Nu\,/\,D \qquad (6)$$

A gas properties table was used to find k_{air} for air at film temperature. All fluid properties are evaluated at the film temperature which is equal to the average of T_{base} and T_{air}

Notice that we have to find *h* before we can determine *Q* so our solution procedure followed the above equation sequence in a somewhat reversed order.

Solution Procedure

A solution sequence was given since there are numerous steps that involve properties and quantities that the students may not yet be comfortable with. That sequence is listed below.

- ? All fluid properties are evaluated at the film temperature which is equal to the average of T_{base} and T_{air}
- ? Find ? at the film temperature and the room pressure from an air properties table.
- ? Determine *Re* using $V_?$, *D*, ?, and (5).
- ? Use *Re* and the table [3] in the text to ensure the validity of the use of (4) for our conditions.
- ? Determine *Pr* at room temperature using an air properties table.
- ? Use *Re* and *Pr* in (4) to determine *Nu*.
- ? Determine *h* using *D* and k_{air} and *Nu* in (6). Care must be taken to use k_{air} and not k_{solid} for this step.
- ? Determine k_{solid} from a materials properties table.
- ? Determine $?_{fin}$, using *D*, *L*, *h*, k_{solid} , and the appropriate equation and curve indicated by the figure [2] in the text. Care must be taken to use k_{solid} for this step.
- ? Calculate *Q* using $?_{fin}$, *h*, *A*, T_{base}, and T_{air} in (3)
- ? Calculate $X_{on\ time\ no\ fin}$ of the hot plate with <u>no fin</u> using (7) and the appropriate time measurements.

$$X_{on\ time} = total\ time\ on/(total\ time\ on + total\ time\ off) \qquad (7)$$

- ? Calculate the $X_{on\ time\ fin}$ of the hot plate <u>with fin</u> using (7) with the appropriate time measurements.
- ? Determine the experimental heat transfer Q_{exp}, through the fin using (8)

$$Q_{exp} = (X_{on\ time\ fin} - X_{on\ time\ no\ fin})\ x\ 650\ Watts \qquad (8)$$

- ? Compare the calculated *Q* with Q_{exp}

RESULTS

Initial trials resulted in heat transfer values derived using Newton's law of cooling being within 35% of the heat transfer values derived from power on times. Further improvement may be made by reducing heat losses by applying insulation around the edges of the base plate and exposing more of the fin to the convection current. Fin temperatures along the exposed portion of the fin indicate a 75% efficient fin whereas the estimate from the chart resulted in a 77% efficient fin.

CONCLUSION

Students have shown a favorable response to the experiment. Many questions arise during the lab session with respect to the meanings of the properties, quantities and calculations. They seem to gain an appreciation for the complexity of the calculations and a sense of accomplishment upon mastering them. They are challenged to account for variations between predicted and experimental results and are able to offer a number of possibilities after careful consideration. No formal assessment mechanism has yet been used to determine the effectiveness of this experiment as a learning tool.

The author feels the experiment is thought provoking, challenging, and is likely to lead to a greater understanding of the mechanism of heat transfer by forced convection.

[1] Çengel, Yunus, A., *Introduction to Thermodynamics and Heat Transfer*, 1997

[2] Figure 8-59 pg. 421 in [1]

[3] Table 10-3 pg. 532 in [1]