Experimental and Analytical Comparison of Internally Finned Pipe with Unfinned Pipe for Heating Applications

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Abstract

This paper presents a capstone project that was done by two MET (Mechanical Engineering Technology) students during their senior year at Purdue Polytechnic, Kokomo. The project objective was to build an apparatus that would allow evaluation of pipes performance in transferring heat from an external heating source wrapped around the outer surface of pipes. The considered pipe set included a normal pipe and another with three longitudinal straight fins soldered to the internal side of the pipe. Heating pads were wrapped around the outer circumference of the pipe providing constant heat flux. The heating pads were insulated using fiber glass insulation. The water flow inside the pipe was controlled to supply same flow rate for all tests while achieving hydrodynamic fully developed conditions. Thermal flow conditions were still developing since the aim of the testing section was to check on thermal enhancement with time. Temperature of water inlet, outlet and along the pipes were recorded for the normal pipe (base case) and compared to the internally finned pipe case using thermocouples embedded through the pipe surface into the center core of flow. The experimental results were compared to numerical results. It was found, on average basis that the outlet to inlet temperature difference increases from 5.3˚F for unfinned pipes to 9.8 ˚F for 3-fins pipes while increasing the pressure drop by 9%. More discrepancy between experimental and analytical results was found for finned pipes. The difference between calculated and measured values were 4% for unfinned and 11% for 3-fins pipes.

Through the implementation of this project, students' performance and project outcomes were assessed against ABET learning outcomes, such as, (1) applying knowledge, techniques and skills to engineering technology activities, (2) applying knowledge of mathematics, science, and engineering to engineering technology programs, (3) conducting tests, measurements, calibration and improve processes, (4) problem solving skills: ability to identify, formulate, and solve engineering problems, (5) team work skills and (6) effective communication: ability to communicate effectively.

Keywords: Internal fins, heating enhancement, analytical simulation, student learning, performance evaluation.

Introduction

Internal fins have been studied for flat plates or as part of heat exchangers for long time. Different shapes and geometries for fins have been adopted. In 1926, [1] suggested parabolic longitudinal fins which was later supported by Duffin [2] in 1956 as reported by [3]. Zhang and Faghri studied fins performance analytically using finite-difference method and they concluded that internal fins can increase the efficiency of thermal energy storage [4]. [5] studied improving the efficiency of a two-dimensional cooling channel used for electronic cooling. They used genetic algorithm in their study.

[6] studied the effect of fin length, thickness, and thermal conductivity on heat transfer and Nusselt number. The study concluded that for short length fins ($L < 0.4$ m), regardless of the thermal conductivity or the material of the fin, the Nusselt number is almost the same for each case. For lengths larger than 0.4 m, the Nusselt number increases with length and thermal conductivity.

In 2004, Kim et al. conducted analytical investigation for internal fins having trapezoidal profile as internal fins for pipes under turbulent flow conditions. The study included various number of fins, multiple fin heights and various helix angles. The study suggested that, regardless of fin geometry, there is a continuum in the governing flow physics [7].

However, most of the studies found in literature were related to internal fins inside flat plates, such as processors or other types of ducts, and for heat exchangers. Very few studies could be found that are related to boilers' efficiencies. For this purpose, the objective of this capstone project was to investigate improvement in heating performance for copper pipes when using internal, straight, longitudinal fins. This will give an indication whether internally finned pipes could increase the heat transfer in boilers.

Research Questions and Methodology

The project problem was basically divided into two parts: (a) unfinned pipe and (b) finned pipe. The project objective was to investigate whether finned pipes can enhance the heat transfer mechanism to the water flowing inside the pipe. This enhancement would be based on an increase in water temperature differences between the pipe outlet and inlet locations. Another important factor that associates with the finned pipes over unfinned pipes is the increase in pressure drop inside the pipe due to the introduction of fins to the internal surface of the pipe.

Experimental Setup

A schematic for the experimental testing apparatus that was built is shown in Figure 1. The team decided to use a ½ inch copper pipe for testing. Heating and testing section was selected to be approximately 1 ft long. Longitudinal straight copper fins, shown in Figure 2a, having 0.01 inch thickness and 0.13 inch height were soldered to the inner surface of the pipe. The fins were soldered at angles of 120˚ apart from each other as shown in Figure 2b. Heating pads with 50 W each were wrapped on the external surface of the pipes and were insulated using fiber glass insulation. A power supply was used to provide power to the heating pads as shown in Figure 3. Water was used as the testing fluid and the water flow rate was controlled using a needle valve, as shown in the final assembly in Figure 5. The flow rate was kept constant for the unfinned and finned pipe testing and was adjusted approximately to 1 gallon per minute (gpm).

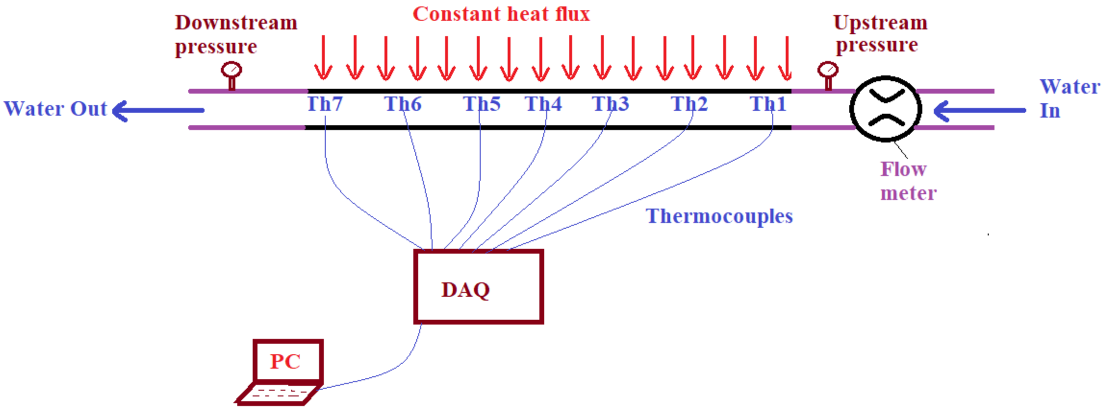

Figure 1. Schematic for the experimental apparatus

Figure 2. (a) copper fin and (b) unfinned and finned pipe sectional sketches

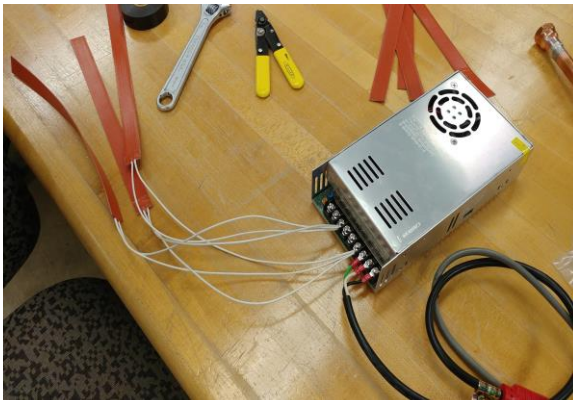

Figure 3. Heating pads connected to the power supply

To measure the inner water temperature at the pipe inlet and outlet and at sections along the pipe, holes were drilled in the pipe as shown in Figure 4a and then thermocouples were inserted inside the pipe before being glued to prevent water leakage as shown in Figure 4b. The thermocouples were connected to a DAQ system that was set to log the temperatures every 30 seconds. Finally, to measure the pressure drop across the pipe, a pressure differential was used across the pipe using pressure transducers. An Arduino was used to log the pressures. High temperature fiber glass insulation was used around the heating pads to ensure the same heat flux is supplied to the pipe and to the water flowing through it. The final assembly is shown in Figure 5.

Figure 4. (a) Copper tube with holes and (b) thermocouples embedded and glued into the pipe

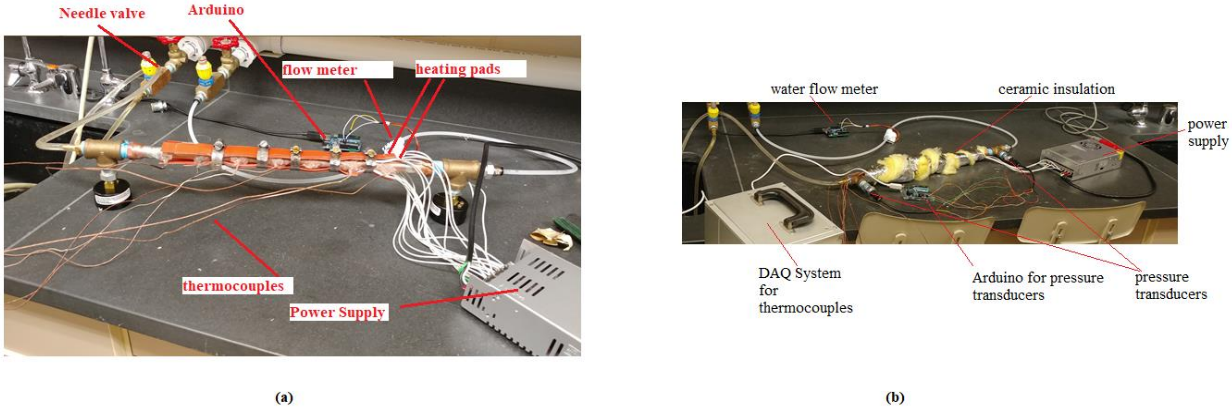

Figure 5. (a) Final assembly showing the heating pads, power supply, flow meter, needle valve and thermocouples; (b) insulation applied and thermocouples connected to the DAQ system

Testing for each pipe case lasted for approximately 3 hours. Data was collected every 30 seconds. The pressure gages shown in Figure 5a were replaced with pressure transducers and were connected to an Arduino to allow data storage as shown in Figure 5b.

Results

The average measured temperatures for all seven thermocouples are shown in Figure 6 for unfinned and 3-fins pipes. The margin of error, based on 95% confidence interval, is also shown around the average values. The calculated temperatures were plotted as well. Calculated temperatures for unfinned pipes along the pipe axis (assuming x-axis is in the longitudinal direction of the pipe) were estimated using equation (1)

$$T_m(x) = T_{m,i} + \frac{q'' P}{\dot{m} C_p} x \qquad (1)^{[8]}$$

where T_m is the mean temperature in ˚F, x is the longitudinal distance in the axial direction of the pipe in ft, $T_{m,i}$ is the mean inlet water temperature in ˚F, q” is the heat flux in Btu/(hr.ft^2), P is the pipe perimeter in ft, $\dot{m}$ is the water mass flow rate in lb$_m$/hr and C_p is the water specific heat in Btu/(lb.˚F).

For finned pipes, the Nusselt number “Nu” is needed to estimate the heat transfer coefficient “h” of water inside the pipe,

$$\mathrm{Nu} = \frac{h\, D_i}{k} \qquad (2)^{[8]}$$

where h is the heat transfer coefficient in Btu/(hr.ft^2), D_i is the pipe inner diameter in inch and k is the pipe material thermal conductivity in Btu-in/(hr.ft^2.˚F). The overall heat transfer coefficient “U” for the pipe and water is given in equation (3) using thermal resistances concept [8].

$$U = \frac{1}{\frac{1}{h} + \frac{(\mathrm{Di-nt})\ln\left(\frac{Do}{Di}\right)}{2k}} \qquad (3)$$

where D_i is the pipe inner diameter in ft, n is the number of fins, t is the fin thickness in ft, D_o is the pipe outer diameter in ft, and k is the pipe material (copper) thermal conductivity in Btu/(hr.ft.˚F). Combining (2) & (3) with the Newton’s law of cooling, shown in equation (4), the local mean temperature could be obtained as shown in equation (5).

$$q'' = U.[T_s(x) - T_m(x)] \qquad (4)$$

$$T_m(x) = T_s(x) - q''\left(\frac{D_i}{k.Nu} + \frac{(\mathrm{Di-nt})\ln\left(\frac{Do}{Di}\right)}{2k}\right) \qquad (5)$$

where $T_m(x)$ is the water mean temperature in ˚F, $T_s(x)$ is the local surface temperature in ˚F, q” is the heat flux in Btu/(hr.ft^2), D_i and D_o are the pipe inner and outer diameters respectively in ft, n is the number of fins, t the fin thickness in ft, and k is the thermal conductivity of the pipe. All parameters can be obtained, except the Nu number. Equation 6, developed by [9] was used to estimate the Nusselt number.

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \left(\frac{Aact,f}{Acore}\right)^{0.1} \left(\frac{Ah,insd}{Ah,n}\right)^{-0.5} \qquad (6)$$

where Pr is the Prandtl number, Re is the Reynold’s number, and $A_{act,f}$ is the actual flow area of flow given by

$$A_{act,f} = \left(\pi \frac{D_i^2}{4} - nA_{fin}\right) \qquad (7)$$

$$A_{fin} = t \times H \qquad (8)$$

A_{core} is the core flow area through an internally finned tube defined as

$$A_{core} = \pi\left(\left(\frac{D_i}{2} - H\right)^2\right) \qquad (9)$$

$A_{h,insd}$ is the inside heat transfer area

$$A_{h,insd} = (\pi D_i - nt)L + (2H + t\,).L.n \qquad (10)$$

$$\underline{A}_{\underline{h},n} = (\pi D_i - nt)L \qquad (11)$$

where t and H are the fin thickness and height, respectively, and L is the longitudinal length of the fin.

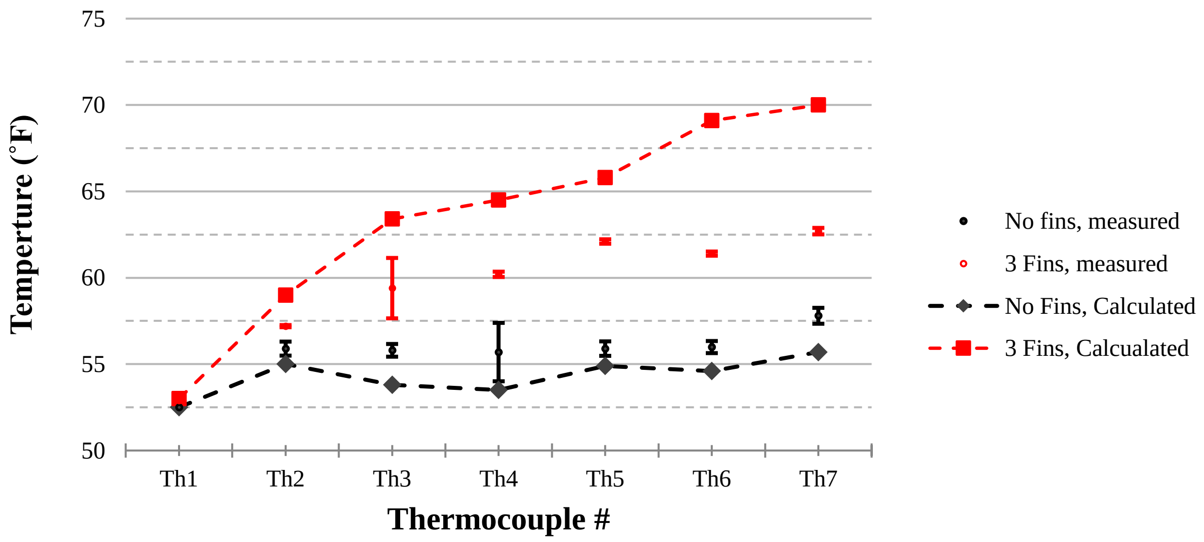

Figure 6. Measured and calculated temperatures (measured temperatures are averages with the margin of error ranges based on 90% confidence interval)

Comparing the measured temperatures for unfinned and finned pipes, the finned pipe provided higher water temperatures and, thus, the total outlet to inlet temperature difference was higher and was enhanced using fins inside the pipe. The calculated results complied with this conclusion, but the values differed from the measured ones.

Discussion

The instantaneous temperature difference between the water inlet and outlet is plotted over the testing period in Figure 7 for both unfinned and 3-fins pipe. It is clear that the average temperature difference with internal fins was higher than the unfinned case. However, the finned pipe needed longer time to see any noticeable temperature increase between inlet and outlet. For example, to achieve temperature differences above 1˚F, the unfinned pipe took 6 minutes, whereas the finned pipe needed approximately 3-times the unfinned case time (≈15 min). However, the internally finned pipe temperature difference rises significantly after that limit and can reach to as high as 9˚F in the following 10 minutes.

On average basis the temperature rise for the unfinned pipe was 5.3˚F against 9.8˚F for the finned pipe. This was almost 85% increase in water outlet to inlet temperature difference. However, the pressure drop in the pipes increased by 9%. It should be kept in mind that this pressure drop might be much higher for longer pipes and, thus, the pressure drop should always accompany the rise in temperature to check on the pump power increase.

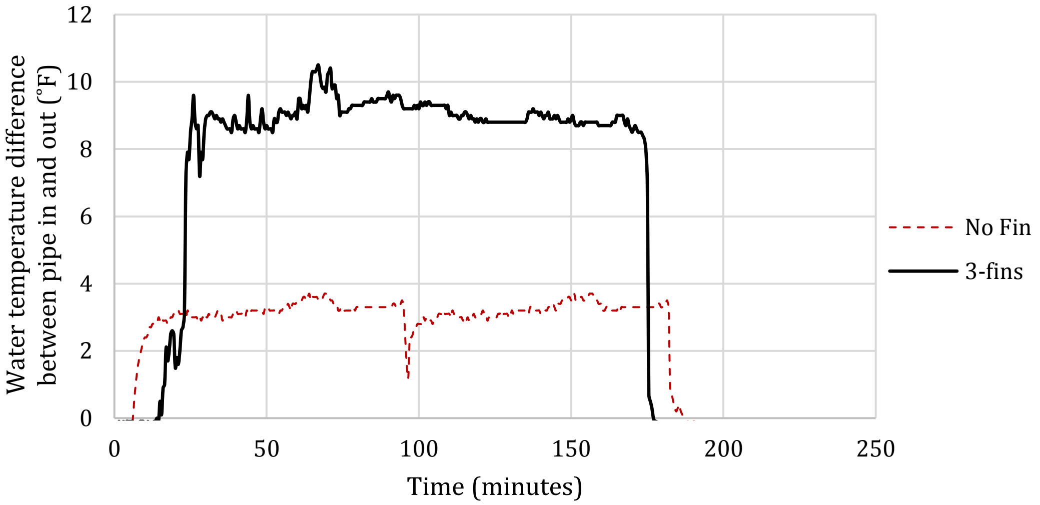

Figure 7. Pipe outlet to inlet water temperature difference for unfinned and 3-fins pipes

The plot in Figure 6 shows that the differences between the average-measured temperatures and the calculated ones were less for the unfinned pipe than for the finned pipe. The difference for each case is plotted in Figure 8. The maximum difference was 4% for unfinned pipes and 11% for 3-fins pipes. This was due to more discrepancies in measurements collected for the internally finned pipe. Also the equations used in equations (6) through (11) might not be the best fit for these fins that had relatively smaller thicknesses than the adopted referred study and lower Reynold’s number, as well. However, all differences were less than 12% which can be considered acceptable taking into consideration the experimental discrepancies.

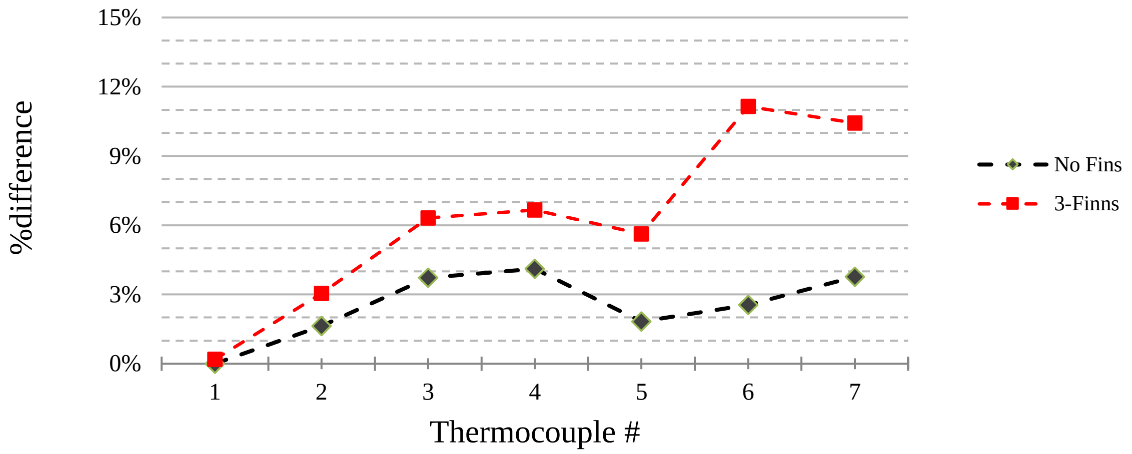

Figure 8. Differences between calculated and measured temperatures for unfinned and 3-fins pipes

Project Assessment

Through the implementation of the project, the students got experience in many aspects needed in industry after their graduation such as brainstorming, preliminary and final design, testing and measurements, and written and oral communication skills. The outcomes of the project were evaluated against ABET learning outcomes summarized in Table 2. Performance assessment and feedback were done through the evaluation of biweekly submitted reports. There were four main categories toward the final GPA of the students: biweekly and final draft reports (15%), final report (50%), presentation (25%), and team work evaluation (10%). The details of the four categories are as follows:

1) Biweekly reports: constituted 15% of the final GPA. These reports summarized the work of the previous two weeks. Each report was recorded on a log-book that included minutes of meetings, weekly list of achieved and pending goals, notes from outside research, calculations, sketches and drawings, test plans, collected data, and analyses.

   Each of the biweekly reports had a general theme as follows:

Report 1	Proposal
Report 2	Conceptual Design
Report 3	Preliminary Design
Report 4	Critical Design
Report 5	Proceed to Test
Report 6	Draft - Final Report

Each report was evaluated based on rubrics given in Table 1.

Table 1. Rubrics used for evaluating biweekly reports

Points	4	3	2	1	0
Weekly notes from supervisor and other parties	Notes exceeded expectations	Notes were appropriately relative to meeting content	Notes qty & quality were missing some meeting contents	Some evidence of notes	No evidence of notes
Legibility	Exceeded expectations	All entries clear & legible	75% or less clear & legible	50% or less clear & legible	25% or less clear & legible
Readability	Exceeded expectations, cross-referenced	Well identified entries	< 75% are identified, erratic flow in places	50% are identified, erratic flow in most places	< 25% identified, erratic flow
Completeness	Well documented, flow and content of entries demonstrated forethought, connections, and results, in and between process phase	75% of flow and content of entries demonstrated forethought, connection, and results	50% of flow and content of entries demonstrated forethought, connection, and results	Flow and content were spotty and unconnected	No evidence of forethought, connections, or results in and between process phases
Lab Notebook Guidelines (items i-viii above)	Followed all criteria	Criteria followed about 75% of the time	Criteria followed about 50% of the time	Criteria followed about 25% of the time	No evidence of following guidelines

The purpose of the draft final report was to evaluate the project and to see the percent completion before the students can give the presentation. This would provide the students with enough feedback for their presentations.

2) Presentation (25% of final GPA): The student presented their projects to interested MET faculty members, guests invited from industry, other students, and parents.

3) Final report (50% of final GPA): submitted by the end of the semester after getting feedback from the project supervisor, guests and other faculty members, who served as external evaluators, and then embedding their comments, suggestions, and corrections in the final report.

4) Team evaluation (10% of final GPA): The remaining 10% of the grade were assigned to team evaluation where the team members evaluated each other and submitted, separately, their evaluation for themselves and other team members. This self-evaluation was half the 10% assigned to team evaluation category. The other half was obtained through oral testing where the instructor asked each team member some questions and evaluated his knowledge to the design, manufacturing and implementation of the project. It should be noted that although the first half of team evaluation contributed to 5% of the final GPA, the final grade of this percentage was decided by the instructor based on results from the team evaluation reports. Since the project supervisor is not able to accurately predict the percentage work done by each member, this evaluation sheet was a secured form that is accessible by the student and the instructor and thus was used by the supervisor to decide if someone did not participate at all. Although this seems to be partially biased, especially when having some personal issues between two members in a team, a confession by more than two members that one team member did not participate fairly would be a strong reason for a low grade for that member. The other 5% assigned for team evaluation was evaluated by the instructor while orally testing and asking each member separately.

Table 2 shows the relation between the ABET learning outcomes and the category/ies that were used to meet these expectations.

Table 2. ABET ETAC students learning outcomes rubrics used for project assessment and the respective means used to meet these outcomes

ABET ETAC Rubric/Learning Outcomes		Means used to meet the rubrics
(1)	Apply knowledge, techniques and skills to engineering technology activities	Final Report and biweekly reports
(2)	Apply knowledge of mathematics, science, engineering, and technology to engineering technology problems	Final report and biweekly reports
(3)	Conduct tests, measurements, calibration and improve processes	Biweekly reports, draft report, and final report
(4)	Problem Solving: ability to identify, formulate, and solve engineering problems	Project proposal and biweekly reports
(5)	Team work	Self-evaluation (described previously)
(6)	Effective Communication: ability to communicate effectively	Presentation and biweekly reports

Conclusions

This work shows an experimental investigation for heat transfer comparison in internally finned circular tubes subjected to constant heat flux. The geometry of the fins were rectangular and parallel to the axis along the pipe. The work was then compared to some theoretical work. The results show significant enhancement of heat transfer due to the usage of internal fins. Temperature rise for finned pipes was slower than unfinned pipes. However, after achieving 1˚F temperature rise, the finned pipe response started increasing sharply at a much faster pace reaching to 9˚F in the 10 minutes following the 1˚F rise which took 15 minutes alone.

The finned pipe showed an enhancement in temperature rise that reached up to 85% over the unfinned pipe and this was associated with 9% in pressure drop due to the addition of the fins inside the pipe.

The differences between the calculated and measured results were higher for the finned pipe than were for the unfinned pipe. The thermocouple location being close to the fins might had affected and offset the results. If one thermocouple is touching the fins, then a hot spot would be seen and it can adversely affect the result. Another reason might be the equations used from literature had limitations over this study such as the Reynold's number and fin dimensions.

Assessment rubrics reflected students expectations from ABET learning outcomes. The capstone assessment should be redesigned to include the other ABET outcomes such as ethics in working environment and to allow better team work evaluation.

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Authors' Bibliography

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