Experimental Investigation of Pipe Heating Enhancement using Different Number of Internal Fins

Maher Shehadi, Ph.D.
School of Engineering Technology, Purdue Polytechnic Institute
Purdue University

Abstract

This paper presents an experimental comparison study done as a capstone project in the School of Engineering Technology at Purdue University. The project objective was to compare the effectiveness of multiple internal fins on heating water flowing inside pipes when subjected to constant external heat flux. The pipes included in the study were a normal pipe, having no internal fins, and three other pipe types with 3, 4, and 6 rectangular and straight fins soldered longitudinally to the inner surface of the pipes. The water flow inside the pipe was controlled by an Arduino and a mass flow sensor to achieve hydrodynamic developed flow conditions but thermally developing. Temperatures of water inlet, outlet and in-between were recorded for the normal pipe (base case) and compared to the three other internally finned pipes. The pressure drop across the inlet and outlet sections of each pipe was also measured and recorded throughout the tests. The finned pipes were shown to enhance heat transfer to the flowing water inside the pipes with the 4-fins pipe showing the best results in terms of fastest response time and highest temperature rise. The pressure drop was observed to increase approximately by 2-3% with each additional fin. Uncertainty analysis were conducted to check on the applicability of the results and was found between ±7-17%.

Students experienced various ABET learning outcomes such as team work skills, problem solving, communication, applying knowledge and technics to engineering technology and applying math, science and engineering to engineering technology, as well. They also had the chance to work in teams which is another outcome of the ABET rubrics.

Introduction

Extended surfaces are widely used with many engineering applications to enhance cooling and heating transfer rates. They are used as heat sinks for electronics devices and used as channels as well. Heat exchangers effectiveness increases while reducing the dimensions and weight of them when associated with heat exchangers. There are different shapes for fins such as rectangular, trapezoidal, and pin. Each one has its own cons and pros.

[1] studied heat transfer performance of circular tubes having six internal longitudinal fins under turbulent and steady flow conditions. The study found significant heat transfer enhancement for the tube with internal fins. [2] conducted a numerical study for steady, laminar heat transfer for pipes having 4-identical fins along their longitudinal axes and subjected to constant heat flux.

The study found that the effectiveness for most fins materials increases along the length of the tube. However, the study indicated that some materials, such as copper, has a little drop in effectiveness near the tube entrance.

[3] conducted an analytical analysis for internal trapezoidal fins inside pipe. The flow was turbulent. The study included various number of fins, different fin heights and helix angles. The study suggested that there is a continuum in the governing flow physics regardless of fin geometry in contrary of what was believed in literature. In 2012, [4] conducted a numerical study for finned tubes while changing the length of fins, their thicknesses, and thermal conductivity. The flow was kept laminar. It was concluded that for short fins when the length is less than 0.4 m, the Nusselt number remains almost the same and would be independent of the pipe material or thermal conductivity. On the other hand, it was found that the Nusselt number increases with lengths beyond 0.4 m with thermal conductivity.

Some applications would necessitate that heat transfer is done while the fluid passes through a pipe and cannot be stored, such as tank-less heating. In other cases, volume and weight of the heat exchangers are an issue, and thus heating must be done as fast as possible in a compact structure.

This project was led by two mechanical engineering technology students in the School of Engineering Technology at Purdue University-Kokomo location. The project is a mix of discovery and learning. On the learning side, the students applied topics learnt in fluid mechanics, heat transfer, thermodynamics, materials and manufacturing in addition to control and measurements techniques. On the research side, the students learnt how to design and build testing experiments to apply a concept. They also learnt how to collect data, interpret and analyze it which can help in increasing the learning outcome levels according to Bloom’s Taxonomy measures. The objective of this capstone project was to investigate pipes heating enhancement using different number of internal longitudinal fins. The team wanted to check on the improvement in the effectiveness of different number of fins by testing 3, 4, and 6 internally soldered fins into the pipes. Applications of similar internally finned pipes can be for boilers, tank-less heating systems, heating exchangers, burners, etc.

Methodology and Experimental Setup

To investigate the effect of internal fins on heat transfer through pipes, the team decided to build a testing station that would allow measuring temperature along the longitudinal direction of the pipe, pressure drops, and flow rate as shown in Figure 1.

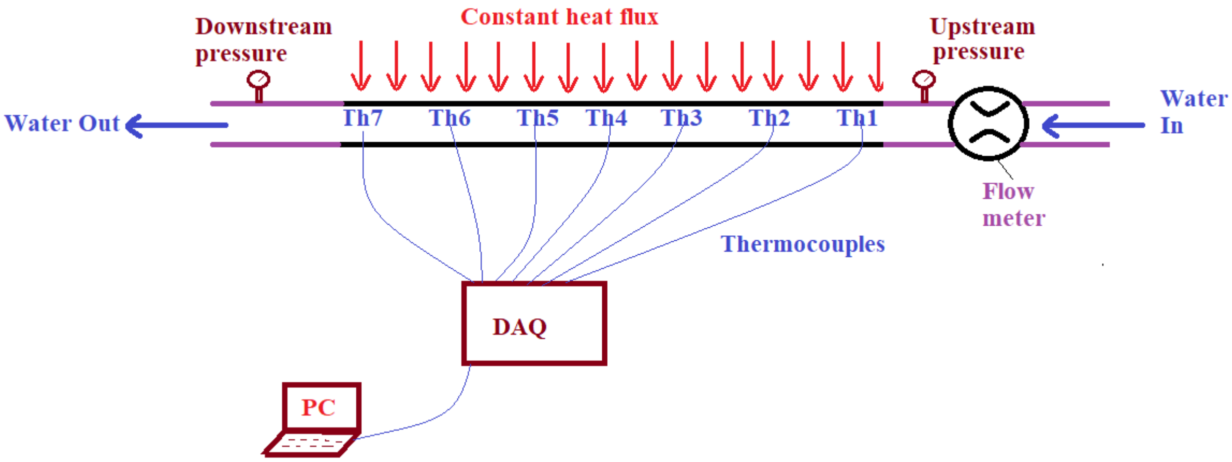


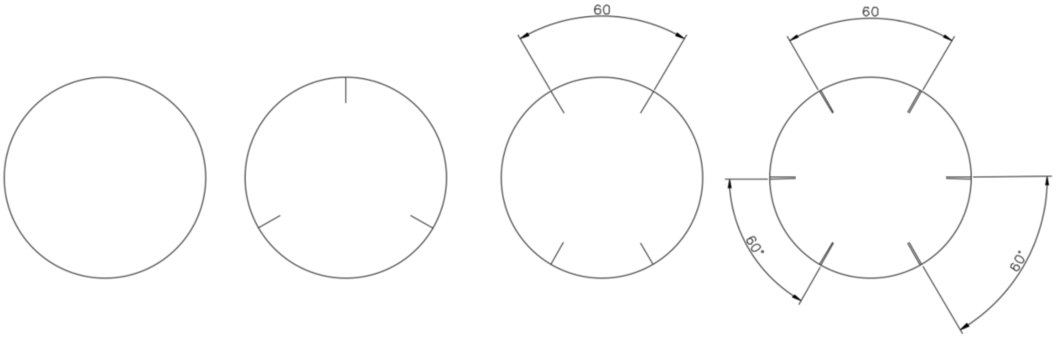
Figure 1. Schematic for the testing apparatus built by the team

The testing would tackle unfinned and multiple finned pipes to check the improvement between different number of fins considered. The team decided to use a ½ -inch copper pipe for testing. A 1 ft long heating and testing pipe section was selected to conduct the tests. Four different testing pipes were considered each one with different number of fins. The first one was the default pipe with no fins, and the other three included 3, 4, and 6 internal fins. The fins were longitudinal, straight, copper fins having 0.01 inch thickness,1/8 inch height and were soldered to the inner surface of the pipe as shown in Figure 2a. Two sweat connections were connected to each end of the testing sections, as shown in Figure 2b that allowed replacement of the testing station easily. The flow rate was controlled using a flow meter and a needle valve as shown in Figure 5.

The fins were soldered at angles of 120˚ apart from each other for 3 fins configuration, were soldered in pairs at 60˚ for 4 fins, and were at 60˚ apart from each other for 6 fins configuration, as shown in Figures 3b, 3c, and 3d, respectively. Heating pads with 50 W each were used at the external surface of the pipes and were insulated using fiber glass insulation. A power supply was needed to provide power for the heating pads as shown in Figure 5. To measure the temperature distribution in each pipe, seven holes were drilled through each pipe, as shown in Figure 2b. Seven thermocouples were installed inside each hole to measure the mean temperature of water flowing through the pipe.

(a) (b)

Figure 2. (a) inner fin soldered into the inner surface of the testing pipe and (b) testing section copper tube with holes made for thermocouple



(a) (b) (c) (d)

Figure 3. Sectional view for the testing pipes with (a) no fins, (b) 3 fins, (c) 4 fins and (d) 6 fins configurations

Glue was applied around the thermocouple holes to prevent leakage as shown in Figure 4. The thermocouples were then connected to a data acquisition system (DAQ) to allow storing the instantaneous temperature readings. The pressure drop across each pipe was measured using two pressure transducers installed at the upstream and downstream the pipe as shown in Figure 4 and Figure 5.

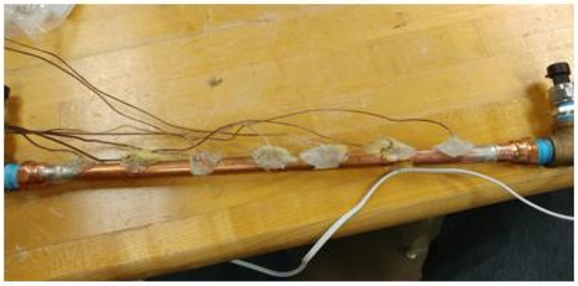


Figure 4. Thermocouples embedded into the center of the testing section

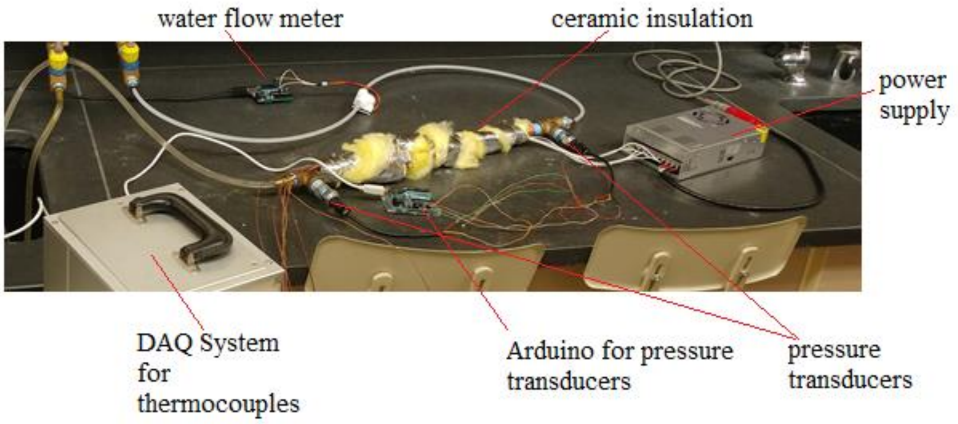


Figure 5. Final assembly for the testing pipe with major parts labeled

The flow rate was adjusted for each case to be approximately 1 gpm. Temperatures were recorded for each pipe case for approximately 3 hours with data collected every 30 seconds.

Results

The average measured temperatures for all seven thermocouples are shown in Figure 6 for unfinned, 3, 4 and 6 finned pipes. The margin of error, based on 95% confidence interval, is also shown around the average values. The confidence interval for the average points were calculated based on 95% confidence level using a t-value of 1.96. The upper and lower limits of each averaged point at 95% confidence interval was calculated according to equation (1).

$$\text{Upper and Lower Limits} = \bar{T} \pm t_{95\%}\left(\frac{S.D.}{\sqrt{n}}\right) \qquad (1)$$

where $\bar{T}$ is the average temperature read by different thermocouples at the same level, $t_{95\%}$ is the confidence interval t-value and is equal to 1.96, S.D. is the standard deviation, and n is the number of samples collected by each thermocouple (n=360). The pressure drop results, read by the pressure transducers, and comparisons are shown in discussion section.

From Figure 6, as expected finned pipes allowed more heat transfer to the water flowing through the pipes than the unfinned pipe. Water flow temperatures recorded inside the 3-fins pipe were lowest compared to the other two finned pipes. However, the pipe with 4-fins provided the highest temperatures and was more than the 6-fins pipe. So on average basis, 4-fins provided the highest heat transfer rate to the water, followed by 6-fins, 3-fins, and then unfinned pipe.

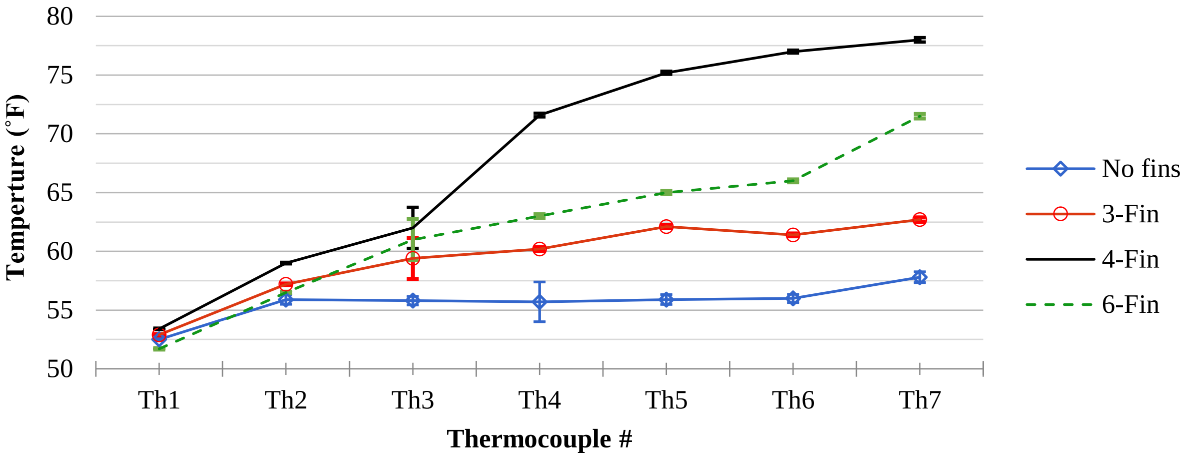


Figure 6. Average temperatures and margin of error intervals based on 95% confidence intervals for various finned and unfinned pipes

Discussion

The water outlet to inlet instantaneous temperature differences for all pipes are plotted in Figure 7. It is clear that the average temperature differences for pipes with internal fins are higher than the unfinned case. Comparing the finned pipes against each other, the 4 and 6 finned pipes are faster in response than the 3-fins pipe. However, the 4-fins was the fastest among the whole other pipe sections and recorded the highest temperature differences. So on average basis, the 4-fins pipe had the fastest response time and scored the highest average temperature difference between water outlet an inlet temperatures, followed by 6-fins pipe, 3-fins pipe, and lastly the unfinned pipe.

The average temperature differences for each pipe sections are plotted in Figure 8 along with the percent increase in pressure drop with respect to unfinned pipe. The average temperature differences increased up to 4-fins but then decreased. This setback in temperature difference for 6-fins compared to 4-fins pipe was probably due to the smaller water flow area with 6-fins compared to 4-fins. Since the water flow rate was kept constant, the water would be faster in the pipe with 6-fins than 4-fins since the area is smaller and, thus, the flow would not have as much time as with 4-fins to reach higher temperatures over 4-fins pipe measurements. For the pressure drop, as expected, as the number of fins increases the pressure drop would increase. Looking into the “percent pressure drop increase w.r.t. unfinned case” curve in Figure 8, it seemed that every fin would cause an additional 3-4% pressure drop increase over that of the unfinned pressure drop. However, looking into the curve after 4-fins, it seemed the curve started to flatten out. To investigate this effect in more details, the pressure drop for each finned pipe case was compared to its predecessor number of fins (i.e. 3 fins to unfinned, 4-fins to 3-fins, and 6-fins to 4-fins). This would give an indication of the effect of each additional fin on the pressure drop under different circumstances and was plotted in Figure 9. The first section up till 3-fins shows that each fin participated towards 3% increase in pressure drop, but beyond that each fin participated towards 2% as the curve dropped to 2%, for an additional fin for 4-fins over 3-fins, and then rises up to 4% for 2-additional fins obtained from 6-fins over 4-fins.

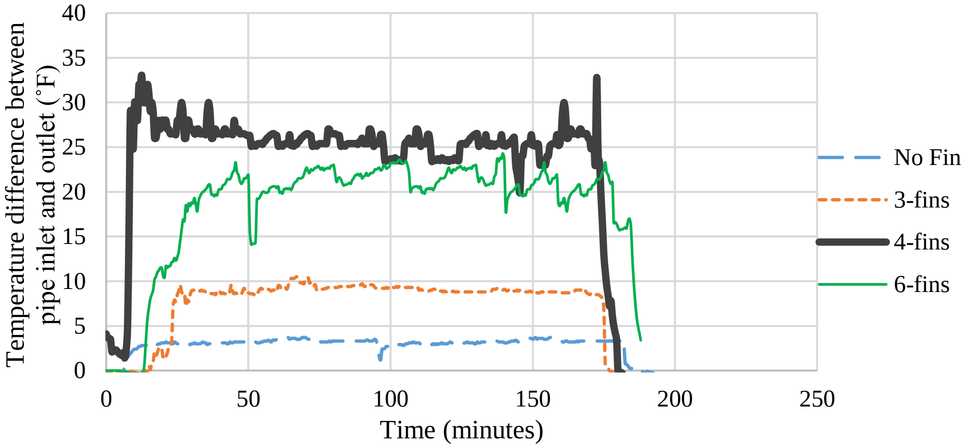


Figure 7. Instantaneous water temperature difference between pipe out and in for different number of fins

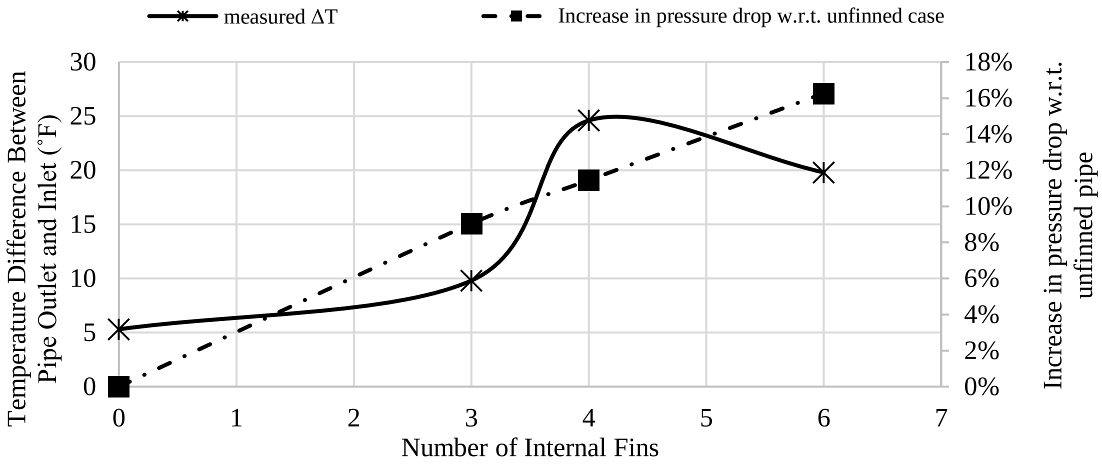


Figure 8. Outlet-inlet temperature difference and percent increase in pressure drop comparisons for different number of fins

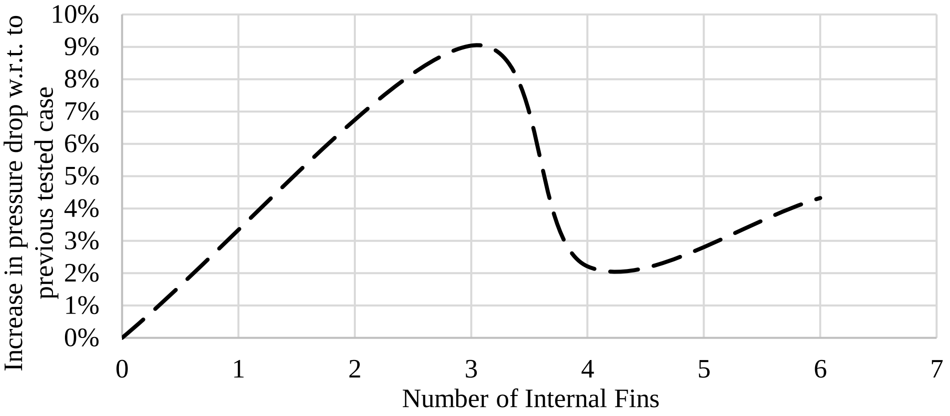


Figure 9. Increase in Pressure Drop w.r.t. previous case

Uncertainty Analysis

The team also looked into the random and total relative uncertainties for the measurements taken. The total uncertainty for each reading collected by each thermocouple was calculated using equation (2), where u_t is the total relative uncertainty, u_{random} represents the error in thermocouple readings and experimental setup, $u_{thermocouple}$ is the thermocouples' uncertainty and was given by the manufacturer: ± 1 °C [2 °F] for temperature ranges of (0 to 133)°C [32 to 270]°F or as ±0.75% of the average temperature measured. Since u is calculated as a percentage, the 0.75% was used for $u_{thermocouples}$, and 5% was used for the u_{DAQ} which is the uncertainty for the DAQ system used to store the data.

$$u_t^2 = u_{random}^2 + u_{thermocouple}^2 + u_{DAQ}^2 \qquad (2)$$

The value of u_{random} was calculated based on equation (1). The total relative uncertainty ranged between ±8-14% for unfinned, ±7-17% for 3-fins pipes, ±8-16% for 4-fins, and ±7-17% for 6-fins pipe.

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	75% of flow and content of entries demonstrated forethought, connection, and	50% of flow and content of entries demonstrated forethought, connection, and	Flow and content were spotty and unconnected	No evidence of forethought, connections, or results in and

	forethought, connections, and results, in and between process phases	results	results		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. This was done before the presentation in order to provide the students with enough feedback for their presentations.

2) Presentation (25% of final GPA): The student presented results of the project to interested MET faculty members and guests.

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. 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, but since the project supervisor is not able to accurately predict the percentage work done by each member, a secured evaluation form that is accessible by the student and the instructor was used 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 equally would be a strong reason for a low grade for that member.

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 capstone project shows an experimental investigation for the heat transfer enhancement in heating pipes using multiple internal, longitudinal, rectangular fins. The flow inside the pipe was controlled to 1 gpm, turbulent, hydrodynamically developed and thermally developing conditions. A constant heat flux was applied to the outer surface of the pipes. The results showed significant enhancement of heat transfer due to the internal fins. The difference in water outlet to inlet temperatures increased from 5˚F, to 10˚F, to 25˚F for unfinned, 3-fins, and 4-fins pipes, respectively, but then dropped back to 20˚F for 6-fins pipe. This was due to the smaller area associated with 6-fins compared to 4-fins which would cause the water to flow faster and, thus, have less time and less exposure to the heat flux. The 4-fins pipe was the fastest in response and provided the highest average temperature difference. However, since the pipes diameter was small (1/2 inch), bigger diameters might behave differently and the results should not be generalized without any further investigation.

The pressure drop was shown to increase by 2-3% for each additional fin. Uncertainty analysis was conducted for all test measurements and the total relative uncertainty, including random, bias, and system uncertainties, ranged between ±7-17% for most cases.

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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Author’s Bibliography

Dr. Shehadi is an Assistant Professor of MET in the School of Engineering Technology at Purdue University. His academic experiences have focused on learning and discovery in areas related to HVAC, indoor air quality, human thermal comfort, and energy conservation. While working in industry, he oversaw maintenance and management programs for various facilities including industrial plants, high rise residential and commercial buildings, energy audits and condition surveys for various mechanical and electrical and systems. He has conducted several projects to reduce CO_2 fingerprint for buildings by evaluating and improving the energy practices through the integration of sustainable systems with existing systems. Professor Shehadi is currently investigating various ways to reduce energy consumption in office buildings by integrating research and curriculum development.