Design, Fabrication and Testing a Heat Exchanger as a Student Project

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1. Introduction

This paper describes the design-fabrication-test of a simple heat exchanger as a final year design project for undergraduate engineering students. Design can be defined as the use of imagination, knowledge, experience and judgement to define a particular end project (1). Much of this activity cannot be taught as a body of knowledge, like an engineering science. Students can only learn to design and gain experience by being actively involved. Hence the need to teach design through projects.

It is important that students realise that they are aiming at the definition of an end product. Many undergraduate design projects end up as paper studies. This is inevitable, owing to the constraints on time and finance within the curriculum. Unfortunately, paper studies do not provide students with the feedback on how well their designs work, or whether they will work at all. Therefore, at Huddersfield, a conscious effort is made to include some projects of a design-fabrication-test nature so that students do have direct feedback on the success, or otherwise, of their designs. One such project, used in the first year of the course, was the design of a compressed air engine (2).

Design is open-ended and the present project reflects this by allowing a wide range of geometries. The type of heat exchanger chosen simulates a car radiator in which hot water flows through a staggered bank of tubes and is cooled by a cross-flow of air. Even when the tube geometry is fixed the students must still determine:

exchanger height
exchanger width
tube pitch
number of rows

The educational goals are to provide a challenging iterative design analysis which is combined with a simple form of construction, that can be built in a short space of time and allowing the integration of CAD/CAM into the design project.

When the project was originally started, the final year design course was based on two major group projects and students were allowed two ‘design weeks’ to concentrate solely on each design project without any other formal teaching commitments. The design weeks provided the ideal opportunity for students to concentrate on the construction of their particular heat exchanger. Over the years, constraints on time and teaching meant that design weeks were reduced. With courses now operating within a modular and semester structure, the luxury of design weeks has disappeared completely. Nevertheless, the heat exchanger project still continues with the specification having been modified to take into account the limited time available for construction.

2. Design brief

The following brief applies to one particular academic year in which the heat exchanger formed part of the general design course. Students were expected to work in groups of four, each group being required to design a cross-flow heat exchanger incorporating several staggered rows of rectangular tubes, to cool water flowing at a rate of 1.5 litres/min from 70°C to 55°C. One type of rectangular tube, nominally 2 x 13 mm was available. There were no limits on the number of water-side passes but the heat exchanger was required to have minimum tube length as a realistic design constraint.

Air-flow was provided at ambient conditions within the laboratory by means of a constant speed fan having an outlet duct 160 mm square and a flow rate of 0.18 m^3/sec. Each group was required to design the necessary tube plates and water headers for manufacture on a CNC machine. The headers to be designed to ensure no leakage of water. During formal testing of the heat exchangers each group attended with their heat exchanger and a transition duct, to connect to the fan outlet. Each group was allowed 30 minutes to assemble the heat exchanger to the rig and carry out five minutes steady state testing during which ambient and water temperature were recorded.

The objectives of the project were to ensure that the design was workable and then to emphasise optimisation. These were reflected in the marking scheme which incorporated 50% for performance, made up of 25% for matching the design specification and a further 25% for optimisation.

3. Discussion

In order to run the project on an annual basis, the specification is changed each year. One of the main changes has been the size and shape of the tubes. The changes prevent students copying solutions from previous years.

The test rig is shown in schematic form in Fig. 1. It consists of a centrifugal fan supplying air flow through a rectangular settling chamber. Since the fan is also used for other projects the design of the settling chamber is to ensure a uniform air velocity at the 160 mm square outlet. The hot water is provided by means of a header tank complete with an immersion heater. Before each test the tank is topped up and the water then brought up to temperature by means of an immersion heater. Each test run uses less than a quarter of the tank full.

Using this technique it is difficult to ensure that the water enters the heat exchanger at exactly 70°C, but any variation can be allowed for by calculating the effectiveness of the actual heat exchanger:

$$E=[Tw1-Tw2]/[Tw1-Ta1]$$

and comparing with the design specification. Water and ambient temperatures are measured using thermometers and the water flow rate by means of a rotameter.

During the thermal design stage students built simple models to simulate their proposed design in order to ascertain the actual fan outlet velocity. Machining of the tube plates and headers is carried out by the University using CAD data from the students and translating for use on a CNC machine. Proficiency in the use of Autocad 2D CAD was assumed from earlier course modules.

This proficiency in the use of CAD assists in reducing the Design to Manufacture lead time whilst introducing students to best practice in CAD/CAM for data integrity and for easy and ready accessibility. For example, the use of the layering system in CAD drawing practice for easy extraction of channels and other features to be machined on the tube plate is encouraged. Layers on CAD can be assigned in order to differentiate between the machining process applied. This layering system can be further applied to allocate layers in accordance to the cutting tool applied from a standard library of tools. This exposed the students to the practical constraints of manufacturing, such as tooling availability and ease of machining that govern the overall product lead time. In practice, a period of three weeks had to be provided between the thermal design stage and start of heat exchanger construction, to allow for manufacture.

4. Thermal design

There are two approaches to designing heat exchangers. Either the mean temperature difference, MTD, or effectiveness-number of transfer units, E - NTU, approach. Over the years, some student groups have preferred the latter but most have chosen the MTD approach as being conceptually more straightforward. For this reason, the design technique described below is based on the MTD approach. The basis equation for any heat exchanger is:

$$Q = UAdTm \qquad (1)$$

where dTm is the mean temperature difference.

Where the temperature changes within the water and air are much smaller than the overall difference in temperature between the fluids, it is sufficiently accurate to take an arithmetic mean temperature difference:

$$dTm = ((Tw_1 + Tw_2) - (Ta_1 + Ta_2))/2 \qquad (2)$$

Using these equations the design can be based on an initial simple heat transfer model, in order to allow the students to rapidly get to grips with the problem, which can then be refined to make it more realistic.

<u>First model</u>

The initial model can be based on three simplifying assumptions:

1. Thermal resistance across the wall of an metal tube is negligible.
2. The heat transfer coefficient on the water-side is very much greater than that on the air-side:
3. The temperature rise on the air-side is very small:

Based upon assumptions 1 and 2 it can be assumed that the air-side heat transfer coefficient controls the design since:

$$U = ha$$

and $$Q = ha\ A\ dTm \qquad (3)$$

The temperature rise on the air-side tends not to be negligible but assumption 3 allows the initial analysis to be simplified whilst incurring errors in the rate of heat transfer of less than 10%.

Data on the air-side performance of rectangular tubes is limited. In practice, the students used information from McAdams (3) on a streamlined section giving an approximate correlation of:

$$Nu = 0.24\ Re^{0.6}$$

where using an equivalent diameter of (perimeter/π)

Using this simple model allowed the students to start the design procedure and to appreciate which variables had most effect on the overall performance. In practice, the tube pitch is a key variable but students had to temper their wish to minimise the pitch with the recognition they actually had to construct the final design.

Second model

Once the student started to understand the thermal design procedure it was necessary for them to refine their design model by including the water-side heat transfer coefficient and the temperature rise on the air-side within their calculations.

The water-side Reynolds number was generally much less than 2000, implying that the flow was laminar. However, due to the shortness of the tubes and the mixing taking place in the headers the students assumed a turbulent flow correlation:

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.3} \quad (4)$$

In practice, the water-side heat transfer coefficient is greater than that on the air-side, but not sufficiently greater as to have negligible thermal resistance. This means that, in order to minimise the tube length, it is necessary to maximise the water-side velocity by reducing the number of tubes in a single pass. This can be achieved by increasing heat exchanger height with relation to the width and increasing the number of water-side passes.

5. Results

The results of the heat exchanger tests are listed in Table 1. The different configurations are illustrated by the three heat exchangers shown in Fig. 2.

The heat exchangers were tested over two days, hence the difference in the ambient temperatures, and numbers represent the order of testing. Since the required duty represents an effectiveness of around 0.3, depending on the ambient temperature, the general level of performance indicates the validity of the air-side data.

Group No	Tube length m	Ambient °C	Water inlet °C	Water outlet °C	E	Comments
1	7.64	20	69.5	54.5	.303	
2	8.56	21	68.5	53.5	.316	
3	7.08	21	72.0	57.5	.294	Single pass
4	8.37	21	71.5	56.0	.307	
5	8.83	21	68.0	52.5	.350	
6	8.46	18	71.0	55.0	.302	
7	9.26	18	71.5	59.5	.224	Air lock
8	9.60	18	72.5	55.5	.385	
9	8.97	18	70.5	59.5	.210	Air-flow
10	8.58	18	71.0	-	-	Major leak

Table 1. Test results

In the event, four heat exchangers failed to achieve the required performance. Number 3 had a single pass arrangement, whereas all the other heat exchangers had two or four water-side passes, and achieved an effectiveness 4% below that specified. It is ironical that if it had been tested on the second day it would have met the specification.

Number 7 had an air lock in one header that prevented the water flowing through all the tubes. Once this was appreciated and a vent plug installed, the heat exchanger was satisfactory.

Poor air flow distribution caused number 9 to fail. The transition duct was hurriedly assembled at the last minute, allowing some of the air to flow past the sides of the tube bank rather than through it. Again, once this was modified the heat exchanger was satisfactory.

It was impossible to test number 10 as it developed a major leak due to silicon bathroom sealant having been used to seal the tubes in the tube plates. The required rebuild could not be implemented in the time available. Although frustrating for the students involved, such failures do reinforce the need for careful detail design.

6. Observations

In reality, the key design feature is the lateral pitch of the tubes. This needs to be minimised in order to increase the air-side velocity between the tubes and, hence, the air-side heat transfer coefficient.

The rectangular tubes were obtained as scrap off cuts from a heat exchanger manufacturer. Unfortunately, this source was no longer available and circular aluminium tubes of differing diameters were purchased for subsequent years. To reduce tube lengths and, therefore, costs the specification was changed to an inlet water temperature of 70°C and an outlet water temperature of 60°C.

Further financial constraints mean that it is no longer possible to purchase metal tubing for this project. It is, therefore, proposed to use drinking straws as a low cost alternative form of tubing. This means that the water temperatures may need to be reduced and that the assumption of negligible thermal resistance across the tube wall is no longer valid.

Bibliography
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Nomenclature

A	surface area, m^2
E	effectiveness
h	heat transfer coefficient, $W/m^2 K$
Nu	Nusselt number
Pr	Prandtl number
Q	heat transfer rate, W
Re	Reynolds number
T	fluid temperature, °C
dTm	mean temperature difference, K
U	overall heat transfer coefficient, $W/m^2 K$

Subscripts

a	air-side
w	water-side
1	inlet conditions
2	outlet conditions

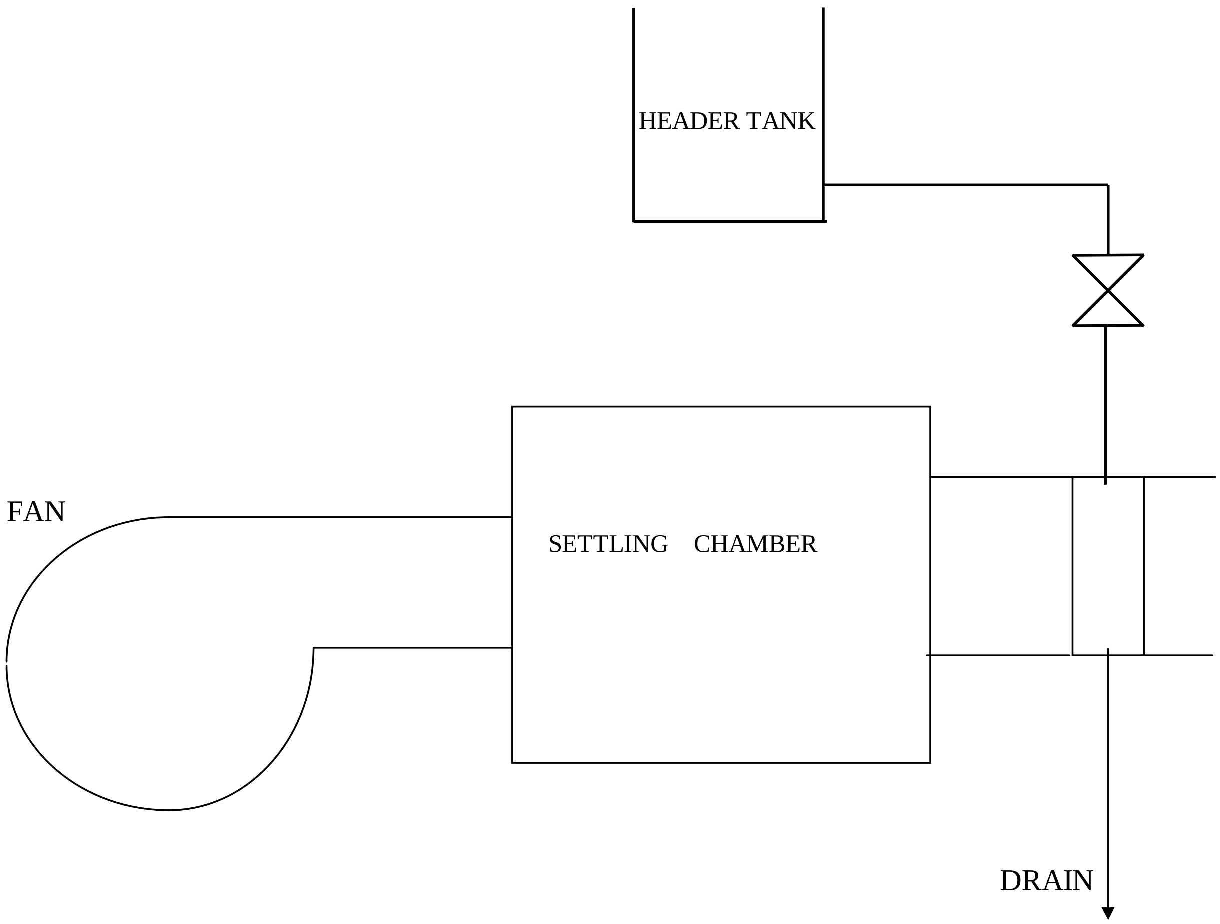

Fig.1 - Schematic form of test rig

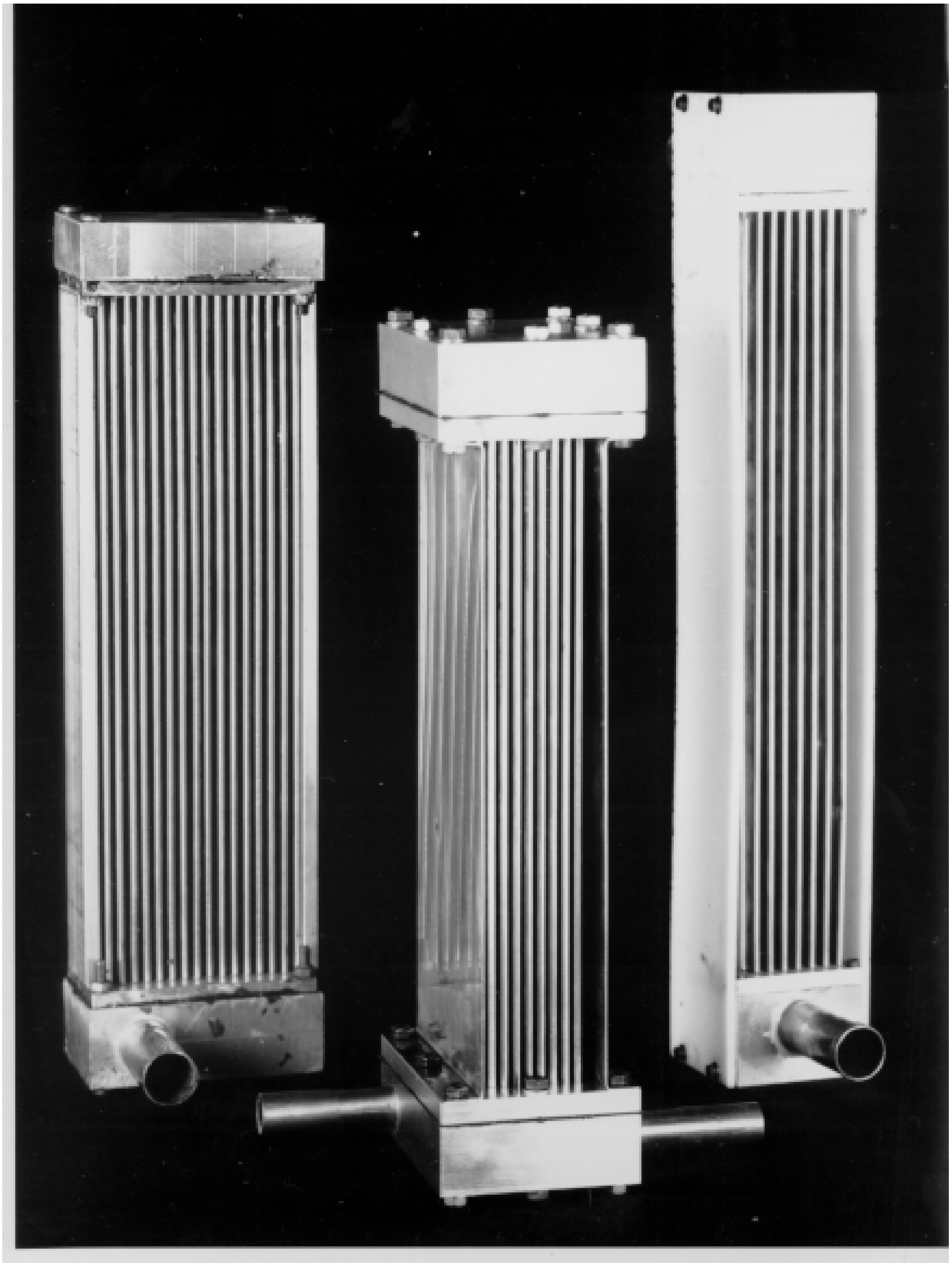

Fig.2 - Three configurations of heat exchanger