Introduction

Griffith University has recently added the mechanical engineering discipline to its offering in the school of engineering. Within the school there is a vision to enhance student learning outcomes, engagement and improve retention through implementation of a student-focused learning approach. A range of project-based learning (PBL) initiatives are to be implemented. These projects range from small embedded projects in traditional courses to wholly continuous assessment courses with a strong PBL focus (Palmer and Hall 2011; Hall et al. 2012). This paper is concerned with a third-year mechanical engineering heat and mass transfer course which was developed using a design-and-build project as the central theme and was run for the first time in 2014.

The PBL approach itself has received much interest (for examples see the reviews by Thomas (2000) and Helle et al. (2006)) and it is particularly attractive for engineering education (Frank et al. 2003; Helfenbein et al. 2012; Krishnan & Nalim 2009; Lima et al. 2007, Mills & Treagust 2003) since PBL can shift the learning process closer to simulating a 'real-world' engineering experience with obvious connections to the desired graduate attributes. Frank et al. (2003) discuss project-based learning as an offshoot from *inquiry-based learning* and constructivist education where students do their own learning and the lecturer takes on a coaching or supporting role to teach students 'how to learn' rather than being a 'provider of facts' to passive listeners. Helle et al. (2006) suggests there are three distinctly different purposes or motivations for implementing PBL in the context of engaging with subject material:

1) Provision of a "very concrete and holistic experience regarding a certain process";
2) Promotion of "integration of subject material" – for example, the students are able to utilize a range of skills and knowledge they have acquired in a 'capstone' project towards the end of a course; and
3) "A method of guided discovery learning with the intention of promoting self-regulated deep-level learning" (Helle et al., 2006).

According to Helle et al., the first of these motivations most often occurs where PBL is used to introduce concepts earlier in a course and the second occurs where PBL is used to tie concepts together. The third appears to be closest to the description by Frank et al. (2003) of PBL. Helfenbein et al. (2012) point out that projects can be embedded in traditional courses in what they describe as 'project-enhanced learning' which can act as a pathway for more traditional lecturers to shift towards a more student-centred learning approach. Luks (2013) describes her own experiences of implementing various 'active-learning' or 'student-centred' techniques in engineering heat transfer classes. Prince and Felder (2006) give an interesting discussion of the different types of inductive learning and teaching.

The motivation for implementing PBL in *3505ENG Heat and Mass Transfer* at Griffith is probably most closely aligned with the first of the descriptions by Helle et al. (2006) listed above in that various aspects of the project were used as concrete illustrations when introducing heat transfer concepts. The second and third motivations were also present, but to a lesser degree. Engineering *thermofluids* courses at Griffith are usually delivered with a more traditional 'chalk and talk' pedagogy (albeit considerably more interactive and student-focused than the dry, passive 'ineffective' teacher-centred learning style that seems to be implied by some authors such as Mills and Treugust (2003) or Frank et al. (2003) as typical traditional engineering education). Thus the present implementation of PBL was motivated by a desire to enhance the learning experience further rather than completely replace the existing pedagogy.

Context

The Course

3505ENG Heat and Mass Transfer is a 13-week, 10 credit-point course with an enrolment of 67 students in 2014. At Griffith, 10 credit points corresponds to one quarter of the typical full-time load for the semester. The majority of the students enrolled were from the mechanical engineering discipline including a small number of international exchange students and a few students from other disciplines who selected the course as an elective. The course was run with a weekly 2-hour lecture and a 2-hour scheduled laboratory time for project work. Because the laboratory required sharing of resources to test and build the heat exchangers, students were also given tutorial problems to solve in the laboratory whilst waiting for access to equipment.

Assessments for the course were as listed in Table 1. The project report (25%) is the assessment item directly connected to the project. Students worked in groups, but all students were required to submit individual project reports.

Table 1: Course Assessments

Assessment Item	**Weighting**
2D Finite-Difference Calculation Assignment	10 %
Mid-Semester Exam	15 %
Project Report	25 %
Problem Solving Assignment	10 %
Final Exam	40 %

The Project

Figure 1 summarizes the project undertaken by the students. The students' task was to work in groups of four or five to design, build and test a double-pipe heat exchanger which was capable of reducing the temperature of hot water with a given flow rate (1.2 L/min) and given inlet temperature (60 °C) by a specified amount (ΔT = 10 °C). Students were given access to an assortment of different tube sizes from which they could select inner and outer tubes. They were then able to cut them to their desired length. The testing of the heat exchangers was done using a test unit (produced by TecQuipment (2014)) which was specifically designed for teaching purposes. Two test units were purchased along with three demonstration heat exchangers which were built for use with the equipment. In the context of the project, the additional 'commercial' heat exchangers were also tested by the students for comparison with their own heat exchangers.

The outer tube material of the students' heat exchangers was copper which made it easy to solder threaded copper t-pieces on the ends to complete the heat exchanger. Construction required dedicated support from two workshop technical officers for about three two-hour sessions during the course to assist in assembly of 14 heat exchangers. Occasional maintenance of the test equipment and repair of leaking heat exchangers was also required for the duration of the course. Most student construction work required repair and/or finishing off by the technical staff to keep in line with the course schedule. Educationally, this was not a problem since 'manufacture' was not listed as one of the learning outcomes for the course.

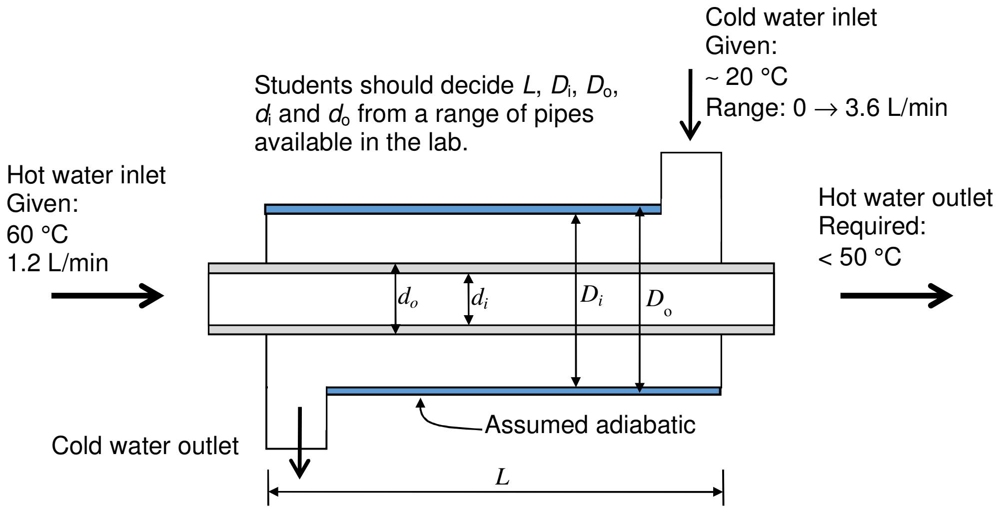

Figure 1: Double-pipe heat exchanger design requirements

Pedagogy

As mentioned above, the present implementation of PBL is best described by Helle et al.'s (2006) first category of a '*very concrete and holistic experience regarding a certain process*'. Various aspects of the project were used throughout the course as introductions for concepts to be grasped within the course material. In particular, the concepts of thermal resistance, external forced convection, internal forced convection, free convection and radiation (as a means of confirming the validity of the adiabatic external surface assumption shown in Figure 1) were illustrated in connection with the project. The more fundamental topics provided the scaffolding required for understanding heat exchanger design. Finally, in week 8 of the course the lecture topic was 'heat exchangers' which was relatively straight forward for the students as a result of their first-hand experience of the device in the project. Because students were already working on the project in advance of the lecture material, the project led to 'anticipation' of lecture content, perhaps in a similar way to that described by Luks (2013) in her implementation of *problem-based learning* in her undergraduate heat transfer course. The project also has pedagogical similarities to Krishnan and Nalim's (2009) strategy for project enhanced learning in a second-year thermodynamics course.

Methodology for analysis of PBL initiative

To gauge the effectiveness of the present implementation of PBL four indicators of performance were considered – feedback from students via student surveys; grade distributions as an indicator of assessed student learning outcomes; correctness of responses on the final exam to questions related or unrelated to the PBL theme; and the practical success of the proposed project (i.e. did the heat exchanger experiment yield meaningful results). The survey results used were the general university 'student experience of courses' (SECs) which students voluntarily complete for every course, every semester as a means of providing feedback to the teaching staff. The survey consists of two open-ended questions and six statements ('questions') to which the students can respond on a five-point Likert scale ranging from strongly disagree (SD), disagree (D), neutral (N), agree (A) to strongly agree (SA). SD has a point value of 1 and SA a point value of 5. The questions are given in Table 2. Survey responses are done online before students take the final exam.

Table 2: University-wide Survey Questions (SEC)

Question (Statement)	Responses
Q1 This course was well-organized.	SD,D,N,A,SA
Q2 The assessment was clear and fair.	SD,D,N,A,SA
Q3 I received helpful feedback on my assessment work	SD,D,N,A,SA
Q4 This course engaged me in learning.	SD,D,N,A,SA
Q5 The teaching (lecturers, tutors, online etc) on this course was effective in helping me to learn	SD,D,N,A,SA
Q6 Overall I am satisfied with the quality of this course.	SD,D,N,A,SA
Q7 What did you find particularly good about this course?	Open
Q8 How could this course be improved?	Open

Approval was obtained from the ethics and integrity team at Griffith University to make use of the student data in this research.

Results and Discussion

Connecting theory and experiment – *a concrete and holistic experience*

All 14 student groups each succeeded to build a working double-pipe heat exchanger which yielded meaningful measured results of heat exchanger performance. Figure 2 shows typical results from a student project. The filled circles and triangle symbols represent the measured temperature difference between the hot water inlet and outlet for the heat exchanger built by the students (operating in parallel flow and counter flow, respectively). The square and diamond symbols are measurements of the performance of the demonstration heat exchangers which came with the test equipment. It was encouraging for the students that in all cases the demonstration 'commercial' heat exchangers performed considerably poorer than the heat exchangers constructed by the students.

Comparing the filled circles with the solid line in Figure 2 shows that the heat exchanger built by the group performed considerably better than was expected from theory. This finding is a good outcome for the learning experience which the students would not get by simply solving heat transfer problems in the classroom. The discrepancy highlights the effect of assumptions in the analysis (such as neglecting end effects which would lead to a significant under-prediction) and confirms the effect of the uncertainty in Nusselt number correlations (which is typically of the order of ± 30 % for practical applications and even greater near the transition region (Bergman et al., 2011)).

The range of flow rates deliverable by the equipment was such that in many cases the theory suggested that there should be a transition from laminar to turbulent flow. The data in Figure 2 is one such example. However, unlike the theoretical calculation there is no obvious transition in the measured data. It turns out that the entrance length becomes very large for laminar flow at higher Reynolds numbers (enhancing heat transfer above the fully developed condition) and the laminar-turbulent transition criteria for flow in an annulus depends on the diameter ratio and not just the Reynolds number. This was an unexpected learning experience for the lecturer as well as for the students.

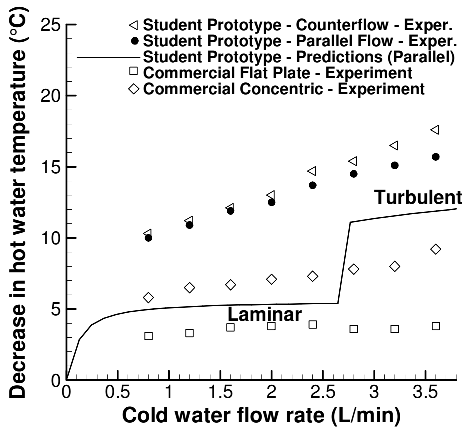

Figure 2: Typical results for heat exchanger performance showing the temperature decrease of the hot water stream. The solid line (predictions) should be compared with the black filled circles.

Overall, the practical implementation of the project can be judged a success. The student-designed heat exchangers all showed a very obvious, measureable temperature drop which clearly changed with flow-rate within rough agreement of simple heat-exchanger theory. Moreover, considering the results from the whole cohort, the tube size combination that was predicted to perform the best did in fact have the highest heat transfer rate. This was surprizing for some students since for most, it was not the intuitive combination of pipes.

Student perceptions of the course

Overall the course was very well received by students. This is shown in Figure 3 which gives the distribution of responses to the first six questions listed in Table 2. In all, 29 (44 %) of the 66 students enrolled in the course responded to the survey. On average the students agreed or strongly agreed that the course was well organized, the assessment was fair, the feedback was helpful, the course was engaging and the teaching was effective. All mean responses, (apart from the course being well organized) were in the top 25% of responses university-wide for similar sized courses. The only question which received any negative responses at all (D or SD) was Q1 'This course was well organized' and even in that case 86 % of response was positive (A or SA).

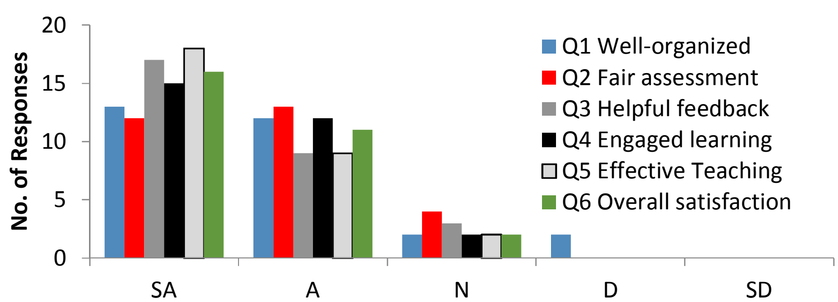

Figure 3: Distributions of responses to the six questions on the student survey

In relation to the PBL component it is difficult to differentiate between its effect and the other pedagogical methods employed in the course. However, the responses for Q4 (This course engaged me in learning) and Q5 (The teaching on this course was effective in helping me to learn) are encouraging since the main role for PBL in this course is to engage the students in learning.

The responses to qualitative questions (unfortunately) did not give a clear indication that the students particularly valued or even recognized the role of the project in the course. Figure 4 summarizes the responses to the open questions (Q7 and Q8 in Table 2) by tallying similar key words or phrases. In relation to 'what the students found particularly good about the course', only two students mentioned the laboratories. The most common response was the 'interesting content' or 'assessments'. However, given that the project played an important role in the content delivery and the laboratory report was worth 25% (and the survey was completed prior to the final exam (worth 40%)) it seems reasonable that the embedded project contributed towards the positive feedback with regard to course content and assessments.

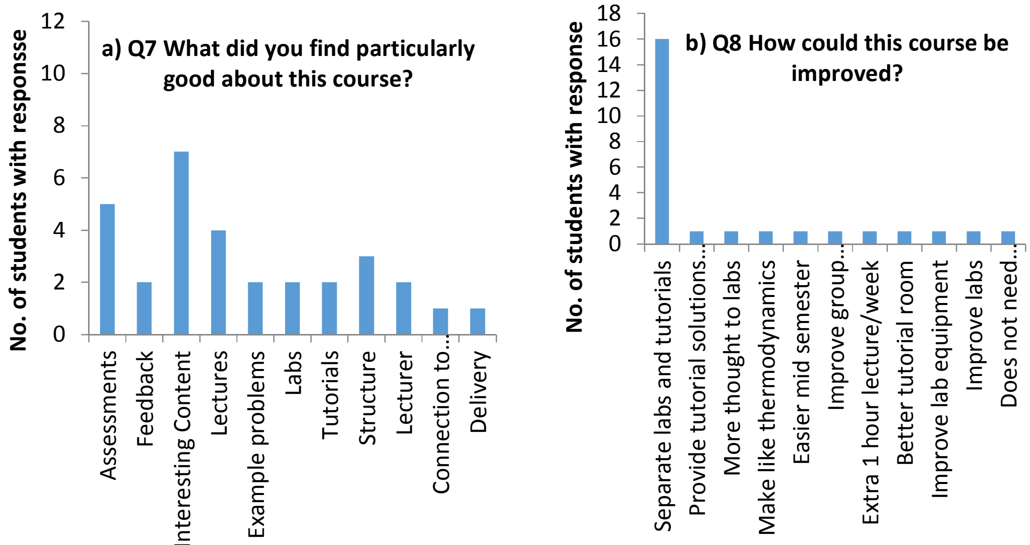

Figure 4: Summary of student responses to the qualitative questions

Figure 4(b) gives a very clear message that the students were not in favour of doing tutorial questions while they waited for access to laboratory equipment. It is possible that this issue stood in the way of clearer direct feedback concerning the project itself. At least two students felt the project needed improvement judging by the comments 'more thought to labs' and 'improve labs' in Figure 4(b). It is possible that these students had different expectations of what should be included in a mathematical core-engineering course. Overall there was a lack of qualitative feedback directly connected to the project embedded in the course.

Learning outcomes

Performances in assessment items are the only direct measurements available for meeting the learning outcomes for this course. Figure 5 shows the grade distributions for the two major assessment items and the overall grade for the course. Overall, students invested considerable effort into their project reports and did a commendable job with approximately 50% of students receiving a distinction (mark ≥ 75%) or higher. The overall grade distribution is also quite pleasing with a peak at the credit level. Students did not do quite as well with the final exam but the distribution of grades still shows less than 15% failure. Thus overall, the course was a success based on measured learning outcomes. It is difficult to say how much of the success can be attributed to the project-based learning component.

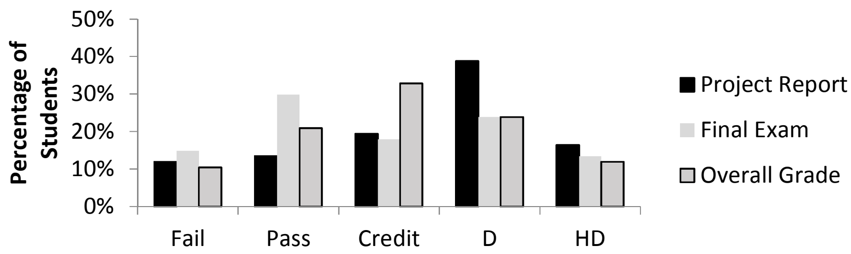

Figure 5: Grade distributions for the project report, the final exam and overall for the course

Another possible indicator for the effectiveness of the embedded project is the student performance on exam questions which are closely related to the theory of the heat exchanger. Figure 6 shows the final exam questions categorized according to topic with the average mark for each question expressed as a percentage of the total possible marks for that question. The exam consisted of seven questions with the heaviest weighting on the last three. Questions 1, 4 and 6 on the exam were most closely related to the project. The students did the best with forced convection (Q1) and the heat exchanger problem (Q4) which is another encouraging indicator in relation to learning outcomes connected to the embedded project. Having said this, it should be noted here that success with exam questions is not always a good indicator of the success of PBL - particularly when 'evaluation techniques do not match the learning outcomes or when grading systems do not reward the behaviors encouraged in PBL' (Luks 2013). Perhaps in future offerings of the course we could include additional conceptual questions and a major question directly on heat exchanger design.

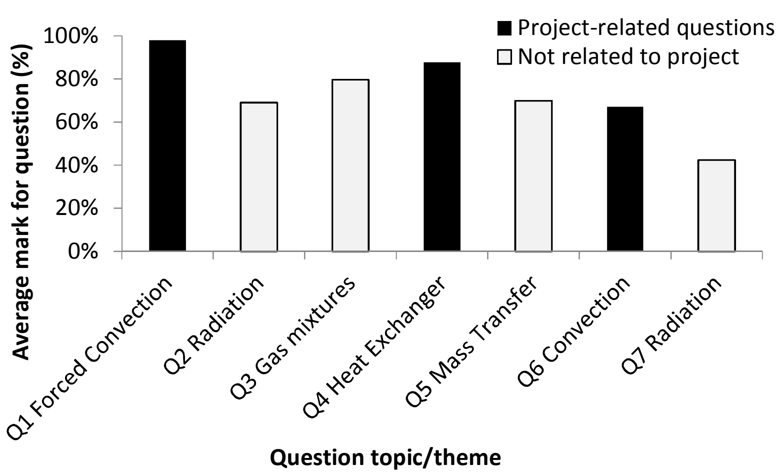

Figure 6 Average marks for individual final exam questions

Conclusion

In this article we were able to describe a successful implementation of a project-based learning component in an undergraduate course on heat and mass transfer. The main merit of the embedded project was in providing a concrete, 'hands-on' experience of heat transfer processes which served as scaffolding for introduction of new concepts within the course material. The students enjoyed the course, engaged well with the project and performed well on all assessment items and exam questions connected to the themes of the project.

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