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Fluid Mechanics Experimental Set-up Designed and Built by Graduate Student for Undergraduates*

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In the presented study, an experimental set-up for use in an undergraduate fluid mechanics laboratory was designed, built and constructed by a graduate student. Two basic educational objectives were determined for this study: to give a good education to the graduate student as both a graduate teaching assistant and as an engineer, and to create a laboratory experiment for undergraduates. Important aspects of experimental studies were introduced to the undergraduate students by using the built set-up, from understanding the basic theory to performing error calculations. The objectives that were fulfilled for the graduate student's education were evaluated using Bloom's taxonomy. The improvement in undergraduate knowledge on the subject was examined by comparing the scores that the undergraduates attained in oral exams that they took before they conducted the experiments with the scores that they achieved from the reports they prepared after they had conducted the experiments.

Keywords: experiment design; laboratory courses; basic fluid mechanics experiments; graduate teaching assistant education; FLOWNEX

1. Introduction

Laboratory applications are important and essential parts of engineering education. They provide the opportunity to make unbounded observations about the characteristics behind the theory. Engineering is a practical profession. Engineers use three fundamental resources for creating technology: energy, material and information. Ever since the early years of engineering education, experimental studies have been very important [1].

Theoretical information can be revised and developed with the help of well conducted basic experiments, so improving the creativity of the researcher or student. There are several reasons to conduct experiments in education laboratories: to introduce a theory, to confirm a theory or to teach measurement methods [2]. Experiments are also the key features in improving science and technology. Although computer simulations have been used to model physical applications, they are limited in making real world estimates because they have often been developed with a great number of assumptions. To verify the simulation codes it is necessary to conduct experiments.

The main aim of this study is to construct an experimental set-up for undergraduate education to be used in the newly formed Thermal Hydraulics and Fluid Mechanics (THFM) Laboratory course of the Nuclear Engineering Department of Hacettepe University (HUNEM). The set-up was built to conduct experiments such as the determination of the friction factor, analysis of the effect of surface roughness on the friction factor, and the investigation of pressure drop for various fittings. This study is remarkable as being the first such experimental study in HUNEM.

The presented study was conducted by a graduate student (also a graduate teaching assistant) as work for her master of sciences thesis, from set-up design to data analysis including the simulations. As future faculty members, graduate teaching assistants (GTAs) need to gain experience in teaching and to learn how to teach. As summarized in the previous studies, within a course environment, GTAs engage in five primary activities: they work in small groups with undergraduate students: they work with undergraduate students in laboratories; they provide academic support for students; they grade homework, exam and laboratory reports and they serve as a second authority figure in undergraduate courses [3].

In some schools, GTAs obtain university-wide introductory education in teaching. Most of the time, they get no feedback or criticism from their professors, and sometimes the university-wide education does not cover the needs of a specific department [4]. In particular, for a GTA teaching in an engineering laboratory, the proper education and applications are important in many aspects, such as the preparation of laboratory manual, conducting laboratory sessions and grading [4]. By taking all

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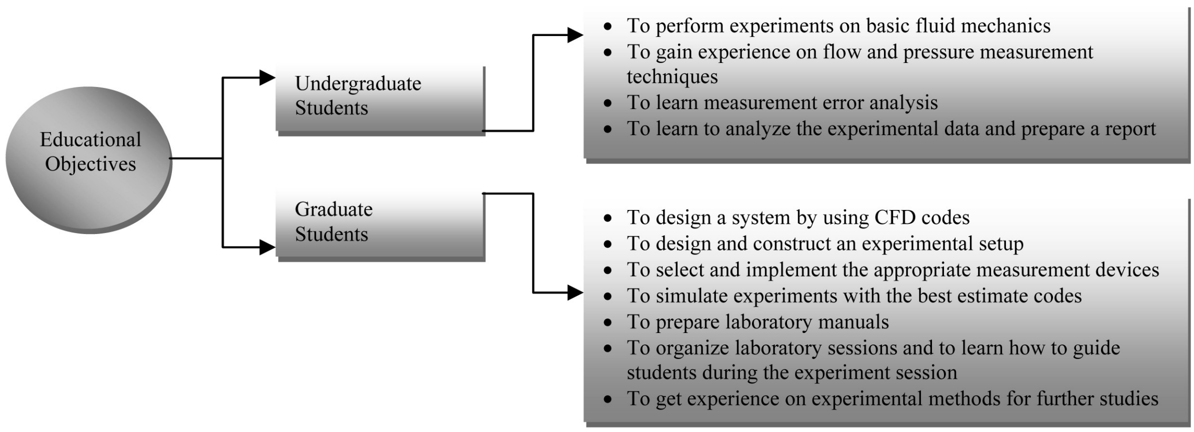

Fig. 1. Educational objectives of the study.

these important issues regarding the education of GTAs into account, another important aim of this study was determined: to give proper education to a GTA who will hopefully be a faculty member who is responsible for a laboratory course that is added to the department's curriculum.

In Fig. 1, the educational objectives of the study are summarized. As shown in the figure, the educational objectives for undergraduate students and graduate students have differences. The aim for the graduate student is to help the student gain experience in experimental methods in the design, construction, performance of experiments and, most importantly, to improve the student's abilities as a GTA and a teacher.

On the other hand, such an experimental set-up fulfils different educational objectives for undergraduate students. These are to observe or to confirm a theory and to conduct experiments on a theory taught in the Fluid Mechanics course, as well as to gain experience of flow and pressure measurement techniques and perform measurement error analysis.

As the result of this study, an experimental set-up was designed and built; related experiments were determined and laboratory manuals were prepared. Furthermore, the associated experiments were conducted and, finally, these experiments were simulated. For the design and sizing of the set-up, FLOWNEX [5], which is a system computational fluid dynamics (CFD) code, was used. The experimental data were then used in RELAP5/SCDAP MOD3.4 [6] simulations.

Once the set-up built was implemented into the THFM laboratory course, the experiments were conducted with the undergraduate students and a survey study was made to learn their opinion on the set-up. The laboratory sessions were reorganized based upon educational objectives and the opinion of the students who had conducted the experiments with the set-up.

Bloom's taxonomy was used by the laboratory course instructor to assess the graduate student as a GTA. The instructor was also the student's thesis advisor. By using Bloom's taxonomy, the graduate student was found to be successful as a GTA.

In this paper, the design and installation of the set-up is first described in detail. Secondly, experiments conducted with the set-up are listed. The results of the repeatability analysis and the experimental results obtained are then presented. Section 5 discusses the results. Section 6 describes the uncertainty analysis, and its importance for data presentation is expressed. In Section 7 the assessment of the graduate student and the opinions of the undergraduate students are addressed. Finally, the results of the study are discussed and concluding remarks are stated.

2. Experimental set-up: design and construction

One of the educational aims of this study was to design and construct an experimental set-up that includes basic fluid mechanics applications and to use this set-up in the undergraduate education curriculum. The design process began with the selection of the theories that were going to be included in the set-up. For this, the basics of fluid dynamics were revised and the appropriate theories and techniques were chosen. A preliminary design was generated by taking the selected theories into account.

The set-up is designed as a closed cycle with a fluid storage tank and a pump. The fluid chosen for use in the set-up is water because of its extensive use in nuclear reactors and its convenience for both its accessibility and low cost. Moreover, considering its wide use in nuclear reactors, stainless steel was chosen as the material for the pipes for the overall set-up. The experimental set-up is divided into three sections. The first section is to determine the friction factor in a straight pipe. The purpose of the second section is to observe the parallel flow characteristics in horizontal pipes. The third section was designed to determine the hydraulic loss coefficients for various fittings.

A preliminary model for the set-up was prepared and was simulated using CFD (Computational Fluid Dynamics) calculations. The results of CFD calculations were used to prepare the experiment matrices and to optimize the dimensions of the set-up. The operating ranges for pressure and flow rate are roughly stated by limiting the Reynolds number using the preliminary model dimensions. By taking the CFD simulation results into account, the Reynolds number was limited to 150 000. FLOWNEX, which is a commercial CFD code, was used for the sizing of the set-up. The preliminary model was demonstrated with the appropriate components of the FLOWNEX and a set of runs was performed for selected cases. FLOWNEX simulations are based on macroscopic balance equations for mass, momentum and energy. FLOWNEX basically solves one-dimensional conservation equations [5].

Each section of the experimental set-up model was simulated. Eventually, the required pump power, pressure range for water circulation through the sections and appropriate flow rate values were determined. Three sections were modelled individually and the combined resultant values were used for sizing.

FLOWNEX was also used to determine the design limitations for the set-up and the working ranges of the measurement equipment. The working ranges for pressure and flow rate were found using the CFD analysis with the limitation of the selected Reynolds number. The maximum design pressure for the system was determined as 2.0 bars and the volumetric flow rate was determined with a maximum value of 4.0 litres per second. Moreover, with the help of the user-friendly FLOWNEX environment, the pressure drop values between any two points were obtained and the measurement points and the working ranges of the pressure measurement equipment were found. When the ultimate design was determined, the test matrix was generated by using the results of the FLOWNEX simulations.

In Fig. 2, the ultimate design of the set-up is shown. The total height of the set-up is 1.80 metres and the total width is 3.0 metres. The highest level of the set-up is easily reachable for a person of average height. A magnetic flow meter (Flow meter 1 in Fig. 2) was placed on one leg and a multi-jet flow meter or a water meter (Flow meter 2 in Fig. 2) was placed on another leg of the set-up. To measure the pressure at significant locations, such as the pump outlet, manometers were used. Finally, for the pressure drop measurement, three differential pressure cells (DP cells) were used with different working ranges. To measure the pressure drop, twenty pressure drop measurement points were placed on the set-up. These pressure drop measurement locations are shown in Fig. 2.

For data collection, a data acquisition system is used with the appropriate computer connections, along with the computer application developed with the ProfiLab program. All data from the measurement equipment are processed with the data acquisition (DAQ) system and they are observed on a computer screen using the developed program. In addition, the pump motor is controlled with a signal provided by the program. To ease pump control during an experiment or to make the pump control more convenient, three pump motor control options are available: the pump can be operated with constant motor revolution speed, constant flow rate or constant outlet pressure options. Feedback for the flow rate data to generate the control signal for the pump motor is gained from the magnetic flow meter. In the same way, feedback for outlet pressure comes from a pressure transmitter placed at the outlet of the pump.

Eventually, the construction of the set-up was completed. The constructed set-up is shown in Fig. 3.

3. Experiments

In this section of the paper, the theory that is taught to the students before they conduct the experiments is described. Although the equations and models listed here are basic fluid mechanics information, they are described in this section in order to show how experiments are matched with the theory.

The first section is prepared to determine the

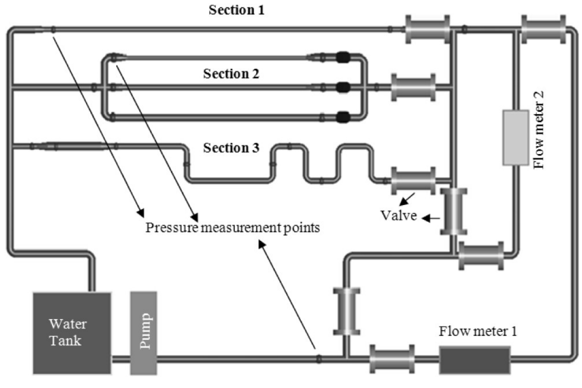

Fig. 2. Model of the set-up.

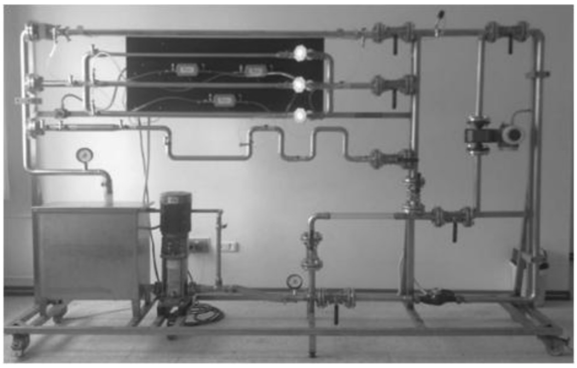

Fig. 3. The constructed experimental set-up [7].

friction factor through straight pipes. For this, a straight pipe that is 1.85 m long and has an internal diameter of 3.2 cm is placed in this section. Three dimensionally equivalent pipes made of different materials are available for this section. The stainless steel straight pipe can be replaced by a copper pipe or a PVC pipe. The purpose is to observe the effect of surface roughness on the friction factor under the same flow conditions.

In pipe flow, friction occurs at the pipe wall. As a result of this, some head loss occurs and this loss is defined by the Darcy–Weisbach equation:

$$h_f = f\frac{L}{D}\frac{V^2}{2g}, \tag{1}$$

where h_f is the loss of head due to friction; L and D are the length and internal diameter of the pipe and V is the mean velocity of the flow. The factor f is the dimensionless friction factor. Although the pressure drop for laminar flow is independent of pipe roughness, it is necessary to take the effect of the roughness of the pipe into account for the turbulent flow. Therefore, the friction factor is a function of the Reynolds number and relative roughness [8]:

$$f = \phi\left(\mathrm{Re}, \frac{\varepsilon}{D}\right). \tag{2}$$

In Equation 2, ε is the roughness of the pipe and the ratio of roughness to pipe diameter is the relative roughness. For a fully developed laminar flow, this function can be simplified as in Equation 3, since the friction is independent of the relative roughness for laminar flow [8]:

$$f = \frac{64}{\mathrm{Re}}. \tag{3}$$

For turbulent flow, due to the complicated relationship between the friction factor, Reynolds number and roughness, the friction factor cannot be determined by theoretical analysis; therefore sets of experiments are conducted and by applying curve fitting to the data, the dependence of the friction factor on the Reynolds number and relative roughness is presented by correlations or with graphical plots.

The experiments conducted to determine the friction factor included artificially roughened pipes. Nikuradse conducted a large number of experiments and collected data. He observed that at high Reynolds number in rough pipes, f becomes a constant that is a function of only the relative roughness [9]. Nikuradse also defined the transition region between laminar and fully turbulent rough pipe flow empirically by making detailed measurements. Von Karman developed an equation to determine the friction factor in 1930 [10]. He used data collected by Nikuradse to confirm his friction factor equation. Integration of the various formulae into a useful structure for commercial pipes was implemented by Rouse in 1943 [11]. Moody found Rouse's diagram inconvenient for commercial pipes.

Moody conducted experiments with commercial pipes and obtained results in a range of Reynolds numbers that includes laminar, transitional and turbulent flow regimes. These experiments did not take extreme conditions into account such as flows with very high velocities, with very low velocities or flow in open channels in which the friction factor depends on the Mach number, Froude's number or Weber number. Moody correlated the original experimental results in terms of the relative roughness of commercially available pipe materials. He represented his studies by a chart which now bears his name, the 'Moody chart' [12]. This chart includes friction factor values in a wide range of Reynolds number and relative roughness. The Moody chart is valid for all steady, fully developed, incompressible pipe flows. Also the Colebrook formula, Equation 4, is valid for all non-laminar parts of the chart and the friction factor can be determined from this formula by solving the equation using iterative methods [8]:

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right). \tag{4}$$

The second section of the set-up is to observe the flow in parallel pipes. There are three parallel pipes in this section. In general, parallel flow is analysed for parallel branches that lie at the same elevation but the parallel flow included in this set-up covers a number of flow resistance mechanisms such as gravity, area change, etc. In this section, the separation of flow through branches can be observed. In

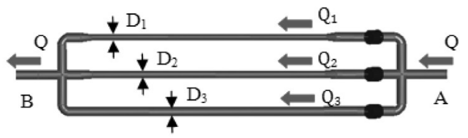

Fig. 4. Flow through parallel pipes.

addition to observation, the flow separation can be manipulated by controlling the flow. The control of the flow is achieved using globe valves placed at the entrance to each branch.

The flow through parallel pipes is a common application among flow systems. The parallel flow in this section can be defined as a flow that divides and subsequently merges again when the pipes are connected as shown in Fig. 4.

As shown in Fig. 4, the sum of the volumetric flow rates at each parallel line is equal to the total volumetric flow rate for incompressible fluids. Therefore the continuity equation for this flow can be represented by Equation 5, where Q is the volumetric flow rate:

$$Q = Q_1 + Q_2 + Q_3. \quad (5)$$

The separation of the volumetric flow rate depends on the flow area of the each parallel pipe and the elevation of the pipe, because of the effect of gravity. The steady state energy equation (Bernoulli's equation), between points A and B, may be rewritten as given in Equation 6:

$$\frac{p_A}{\gamma} + \frac{V_A^2}{2g} + z_A - h_i = \frac{p_B}{\gamma} + \frac{V_B^2}{2g} + z_B. \quad (6)$$

In the Equation 6, the head loss due to friction and the pipe fitting elements are included in h_i. In the equation, γ represents specific weight, while g is gravitational constant.

The main aim of the third section is to observe the pressure losses on the fittings. The pressure drops on the 90° elbows are measured and hydraulic loss coefficients are determined. Also, there are other turn fittings, which are constructed by arranging the small pipes and elbows, such as C-shape bends and S-shape bends. A C-shape bend is a fitting that is used to change the direction of the flow to the opposite direction. On the other hand, an S-shaped bend does not change the direction of the flow but changes its elevation. In addition to loss coefficients for turn fittings, the pressure gain due to pipe enlargement is examined. The pressure loss coefficient of fittings, K, is defined using Equation 7, which is also known as the Darcy equation:

$$K = \frac{h_l}{V^2/2g}, \quad (7)$$

where K is the loss coefficient, h_l is the fitting head loss, V is the average upstream velocity at the inlet of the fitting and g is the gravitational acceleration. The head loss of a fitting is determined by using the mechanical energy equation. The general form of mechanical energy equation written between two measurement points is used to estimate the loss coefficients for fittings:

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + \sum_i \frac{f_i L_i}{D_i} \frac{V_i^2}{2g} + h_i, \quad (8)$$

where f is the Darcy–Weisbach friction loss coefficient of the pipe connected to the fitting, D is the diameter of the pipe and L is the length of pipe between the pressure measurement points.

4. Repeatibility analysis

To assess the repeatability of the experiments and the stability of the apparatus to measure the differential pressure and flow rates, selected experiments were run for six times. The selected experiments are: the estimation of the friction factor in the first section, the hydraulic loss coefficient determination of the 90° elbow and the determination of the expansion coefficient in the third section. In this part of the paper, the results of an experiment, repeated six times, to measure pressure drop through a 90º elbow are presented.

After each test, the DP cell jacks were disconnected from the measurement points, the water that filled the arms was evacuated, filled and replaced and then the measurement process was repeated. The repeatability of the experiments was tested by comparing the hydraulic loss coefficient of the 90º elbow. Figure 5 illustrates the K-values obtained from the six tests versus the average velocities. In Fig. 5, the measurement uncertainties are also presented as error bars. (The calculations performed for the uncertainties in the measurements are described in Section 6.)

As Fig. 5 indicates, at higher velocities the difference between the K-values evaluated present differences; the maximum difference between two K-values obtained from different runs is about 0.02. The results obtained by conducting these experiments and the other repeatability experiments show that the data obtained by using the set-up with same conditions at different times are in good agreement with each other, therefore the experiments are repeatable.

5. Experimental results

In this section, the results of the conducted experiments and data obtained are presented. In the

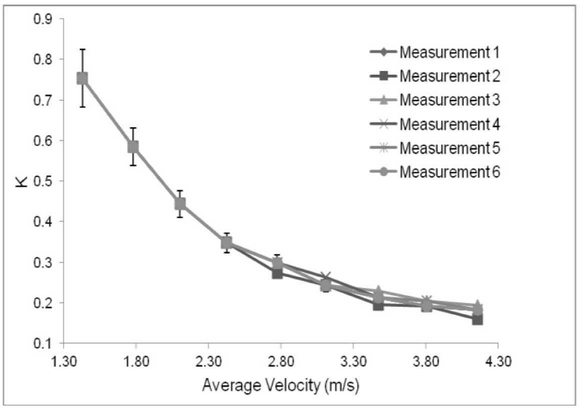

Fig. 5. Repeatability for hydraulic loss coefficient of an elbow.

figures presented in this section, the measurement uncertainties are also shown.

5.1 Results of the experiments conducted for the friction factor determination

In this section, the friction factors for the pipes that have identical dimensions but are made from different materials are obtained. The change in friction factor with the change in the Reynolds number and roughness is analysed. In the light of the theory, it can be admitted that the determination of the friction factor is strongly based on the pressure drop measurements. Pressure drop measurements were performed as explained in the previous sections. The friction factor behaviour is reported as a function of the Reynolds number in the literature. Hence, the friction factor values obtained for different pipes, made from different materials, are presented using the Reynolds number.

The commercial stainless steel, copper and PVC pipes have different roughnesses. The standard roughness values for stainless steel, copper and PVC pipes are given in Table 1. Stainless steel has the highest roughness of the materials used in the set-up. The roughness of commercial stainless steel is three times greater than that of copper and thirty times greater than that of the PVC pipe as presented in Table 1.

Based on the roughness information given in Table 1, it can be seen that the stainless steel has the highest friction factor and the friction factor of the PVC pipe is the lowest for the flows with same Reynolds number. Figure 6 shows the effect of roughness on friction factor. The values of the friction factors for stainless steel, copper and PVC pipes are compared in Figure 6. As the relative roughness decreases, the value of the associated friction factor decreases. The results presented in Fig. 6 and data presented in Moody chart [12] are in good agreement in presenting the linear decrease in friction factor with increasing Reynolds number.

Table 1. Roughness of the pipes

Pipe material	Roughness (μm)
Stainless steel	45
Copper	15
PVC	1.5

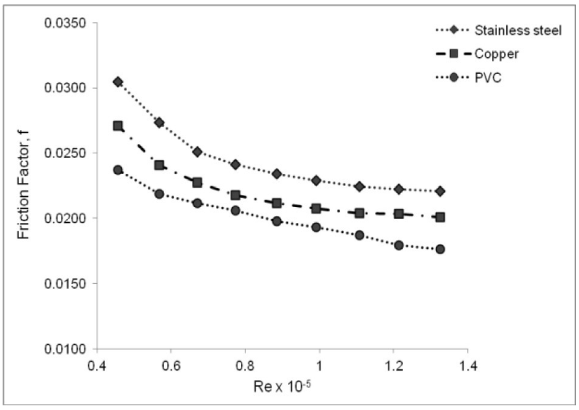

Fig. 6. Friction factor graph.

5.2 Results of the experiments conducted for the parallel flow observation

The basic aim with this section is to observe the separation of the flow in the branches. For this reason, two experiments were conducted and the flow separation was observed for various combinations of branches with the help of globe valves. The branches are named according to their elevation (the upper branch is Branch 1, middle one is named as Branch 2 and lower one is Branch 3). Figure 7 shows the fractional volumetric flow rate in Branches 1 and 3. The fractional volumetric flow rate in Branch 1 is about 65% on average and in Branch 3 is about 35%. At the branching point, a substantial fraction of the total volumetric flow rate goes towards Branch 1.

Figure 8 shows the fractional volumetric flow rate in Branches 1 and 2. The fractional volumetric flow rate in Branch 1 is about 75% on average and in Branch 2 it is about 25%. At the branching point, a substantial fraction of the total volumetric flow rate goes towards the Branch 1.

The difference in elevation between Branch 1 and Branch 2 is 20 cm and between Branch 1 and Branch 3 is 40 cm. It is observed that the effect of flow area on the flow separation is more dominant than the effect of gravity.

5.3 Results of the experiments conducted for the hydraulic loss coefficient determination

This section of the set-up includes the determination of the hydraulic loss coefficients for various fittings. The fittings examined are a 90° elbow and a gradual

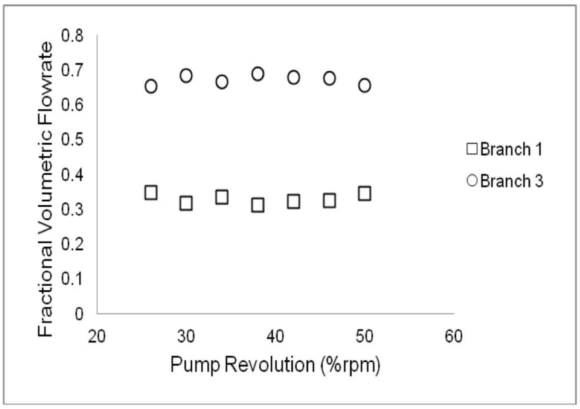

Fig. 7. Branching of the flow in Branches 1 and 3.

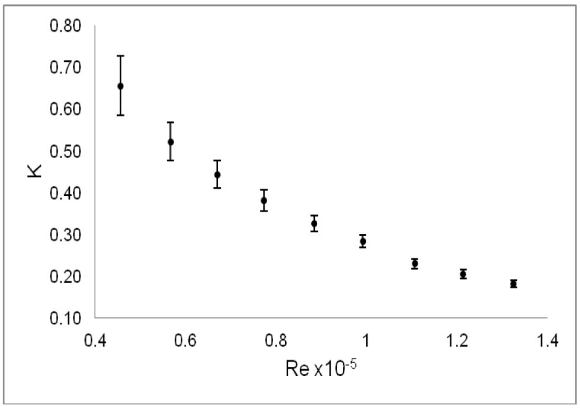

Fig. 9. Hydraulic loss coefficients for the 90º elbow.

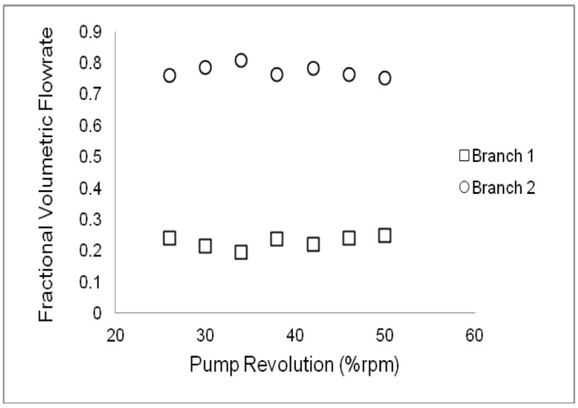

Fig. 8. Branching of the flow in Branch 1 and 2.

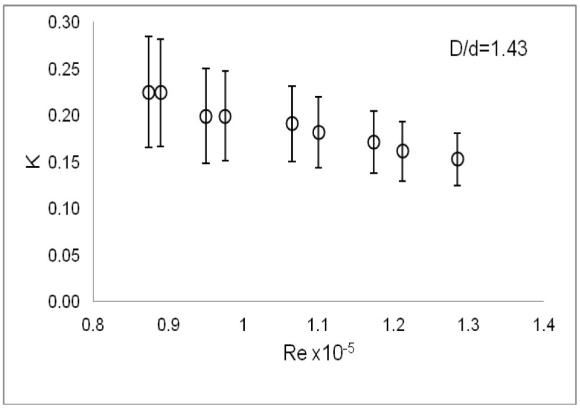

Fig. 10. Expansion coefficients for gradually enlarging pipe.

expansion in pipe diameter. As in the determination of the friction factor, the determination of the hydraulic loss coefficient is directly related to the pressure drop measurements. The hydraulic loss coefficient values are reported as a function of the Reynolds number in the literature. Hence, the hydraulic loss coefficients were reported using the Reynolds number and compared with the literature. For comparison, the results of Idelchik's experiments [14] are used, since these results cover a wide variety of fittings.

The examined 90° elbow changes the direction of the flow from the lower to the higher elevation. Figure 9 presents the hydraulic loss coefficients. The hydraulic loss coefficient for this elbow increases significantly as the Reynolds number increases up to a Reynolds number of 130 000. From this point, the increase in hydraulic loss coefficient slows down, obviously. Depending on the range of Reynolds number and relative roughness values, the trend in Fig. 9 is consistent with Idelchik's data [14].

The expansion coefficient of the gradually enlarging pipes can be categorized according to the diameter ratio of inlet to outlet and the angle of enlargement. In the set-up used for this study, the enlargement angle is 60° and the outlet to inlet diameter ratio is 1.43. Figure 10 presents the change in expansion coefficient with the change in Reynolds number. The expansion coefficient decreases as the Reynolds number increases. According to Idelchik's results, it can be inferred that the expansion coefficient decreases via the increase in Reynolds number, but it does not change significantly. As shown in Figure 10, the expansion coefficient does not change significantly, although the trend shows a decreasing behaviour. Thus, the estimated expansion coefficient values are consistent with the results of Idelchik's experimental data [14].

6. Uncertainty analysis

The uncertainty is a property of the testing that depends on all the contributing measurements. Uncertainty analysis is an essential part of any scientific experiment [15]. Uncertainty analysis was performed for the estimation of the hydraulic loss coefficients of the fittings and the friction loss coefficients of the pipes. The pressure and flow rate were measured by using the DP cells and magnetic flow meters. The measurement errors associated with the measurement equipments are assigned by the manufacturers. The measurement error is 1.0% in full scale for DP cell measurements [16]. Although the DP cell measurement error is constant for all ranges of the measurements, the error of the volumetric flow rate measurement varies due to the flow rate. For example, the measurement error value is 0.6% for a flow velocity of between 0.6 and 2.0 m/s, 0.55% for a flow velocity of 2.0 to 3.5 m/s and 0.5% for a flow velocity of 3.5m/s and so on [17]. Because the derivation of the loss coefficients depends on flow velocity and pressure drop measurements, the effect of measurement errors on the loss coefficient determination are analysed with the standard error propagation rules [18]. The hydraulic loss coefficient is determined by Equation 7. By applying the error propagation rules, Equation 9 is obtained for the estimation of the uncertainty in the measurements:

$$\sigma_K = \sqrt{\left(\frac{\partial K}{\partial \Delta P}\right)^2 \sigma^2_{\Delta P} + \left(\frac{\partial K}{\partial V^2}\right)^2 \sigma^2_{V^2}}. \quad (9)$$

In the above equation, σ_K is the uncertainty in calculated hydraulic loss coefficient, K is the hydraulic loss coefficient, ΔP is pressure drop, V is average velocity in the pipe and $\sigma_V 2$ is the measurement error in velocity squared. The measurement errors strongly depend on the measuring equipment used and the experimental conditions. The analyses the uncertainties in measurements are one of the crucial parts of presentation of the data. Hence, the error analysis is an important part of the education of the students to improve their experimental skills. With this knowledge, students will be able to obtain data by experimental methods and represent data more accurately.

7. Discussion

In this study, an experimental set-up was designed and constructed by a graduate student for undergraduate student use in the Nuclear Engineering Department of Hacettepe University. For the design, the computational fluid dynamics code, FLOWNEX, was used. CFD calculations were used for both the design and specification of the experimental procedures. After the construction, the experimental procedures were finalized. The educational objectives were stated with the help of the considerations taken into account during the design process and the results from the experiments were obtained. Laboratory manuals were prepared with respect to the educational objectives. Table 2 summarizes the educational objectives for both the undergraduate and graduate students and the actions by which the objectives were achieved.

7.1 Objectives fulfilled for the graduate student

As mentioned earlier, one of the objectives of the study is to give a proper education to a graduate student as an engineer and as a teaching assistant.

The assessment of the graduate student as a teaching assistant was done by using Bloom's taxonomy. As a widely used educational assessment tool, Bloom's taxonomy is useful to observe whether a learner can practise satisfactorily in a higher cognitive domain [19]. The practices of the Bloom's taxonomy and the ways that they are achieved by the graduate student are listed below.

- *Knowledge*: Preparation of the theory sections of the laboratory manuals through making necessary definitions, derivations and preparing a summary of the literature
- *Comprehension*: Revision and correction of the laboratory manuals by taking the responses of the undergraduate students and the professors.
- *Application*: Preparation of the oral exam questions and conducting oral exams
- *Analysis*: Making comparisons, explaining cause and effect relationships and matching theory and measurements during the oral exams and experiments
- *Evaluation*: Preparation of the manuals and laboratory sessions
- *Synthesis*: Grading the oral exams and reports prepared by the undergraduate students

The graduate student's achievements for the above listed practices were assessed by the instructor of the laboratory course (also the student's thesis advisor) through revision of the laboratory manuals, observations of the oral exams and revision of the grading of the reports. The graduate student was found to be successful as a teaching assistant to conduct fluid mechanics experiments with undergraduate students, to assess their performances during oral exams and to grade their reports.

As an engineer, the graduate student learnt to use a commercial CFD code to design a system. In addition, the student designed the set-up by taking the basic fluid mechanics concepts into account and selecting the proper measurement equipment. By simulating the experiments the student learnt how to use a best estimate code. The graduate student who completed this study gained valuable experience on designing experimental set-ups and their real life applications. In her future studies, more complex experimental set-ups that are based on more complicated phenomena will be designed with the help of the experience gained with this study.

Table 2. Achievement of educational objectives

	Objective	Achieved by
Undergraduate students	• To conduct experiments on basic fluid mechanics	Students conducted four experiments with the set-up.
	• To gain experience on flow and pressure measurement techniques	One of the experiments especially covers measurement techniques.
	• To learn measurement error analysis	In each experiment, students are responsible for the calculation of the uncertainties in measurements at each analysis they performed.
	• To learn to analyse the experimental data and prepare a report	After laboratory sessions, each student is responsible for writing his/her own report. In the report, he/she has to analyse the obtained data in laboratory session and represent the results with his/her concluding remarks.
Graduate student	• To design a system by using CFD code	FLOWNEX (CFD code) was used for design of the set-up and determination of the working ranges.
	• To design and construct an experimental set-up	The set-up was successfully designed and constructed.
	• To select and implement the appropriate measurement equipment	The appropriate measurement equipments for the stated experiments and working ranges were implemented to the set-up.
	• To simulate experiments with the best estimate codes	Performed experiments were simulated by using RELAP5/SCDAP MOD3.4.
	• To prepare laboratory manuals	Laboratory manuals were prepared under the titles of the four experiments.
	• To organize laboratory sessions and to learn how to guide students during the experiment session	Laboratory sessions were organized for groups of undergraduates and sessions were revised according to students' opinion. During the sessions, oral exams were performed to create a contact between the theory and the experiments.
	• To get experience on experimental methods for further studies	The whole of this study was performed by a graduate student who wants to continue studying experimentally. This study was a basic step for more complex experimental studies.

7.2 Objectives fulfilled for the undergraduate students

The experimental set-up was implemented into the THFM Laboratory of the HUNEM in 2011 Spring semester. The experiments were divided into four parts and all four parts were performed in one laboratory session. As a part of THFM laboratory, the experiments fulfilled the lack of basic fluid mechanics applications. In addition to the basic theories, the measurement techniques were also examined by the students. Each laboratory session was conducted with one laboratory group made up of three or four students. In order to check the students' background knowledge on the topics of the experiments, an oral exam was conducted at the beginning of the laboratory sessions. The content of the oral exam comprised the theories on which the experiments are based and the operation of the measurement equipment. Students were also asked to prepare a report on the experiment after the session. The oral exam was the first measure of the knowledge of the students on the topic, and the experiment report was the second measure.

According to the oral exam scores, 60% of the students were successful in the exam and the students' background on the theories of the experiment was adequate to conduct and to understand the experiment. On the other hand, their background was inadequate to understand the details of the experiments and to perform the statistical error analysis. For this reason, the graduate student gave a brief lecture on possible error sources and error analysis. Forty percent of the students failed the oral exam and took the exam again in another session.

The content of the reports prepared by the students included a summary of the basic theory required to conduct the experiment, information on the measuring devices and their properties, representation of the data obtained, calculation procedures and measurement error analysis, representation of the results and a detailed discussion section on the results of the experiments. Ten percent of the students were found to be unsuccessful according to their reports and they were tasked with preparing a second report. Ninety percent of the student prepared successful reports.

Results show that the knowledge of the students on the theories behind the experiment was significantly improved. Measurement error analysis was introduced to the students during the session and the majority of the students were able to correctly implement it for data obtained from the experiment.

The opinions of the undergraduates were crucial to improve and modify the experimental procedure of the laboratory session. For this reason, a survey study was conducted among the twenty-five undergraduates who conducted the experiments. The results of the survey showed that it is certain that this experimental set-up aroused the curiosity of the student and that the students had found the set-up interesting. The students agreed with the idea that it is very useful to practice on the measurement techniques. Eighty-eight percent of them said that they had a good time during the session. Eighty-four percent of the students indicated that this set-up encourages students to experimental studies. They found the associated experiments paralleled the theoretical lessons on Fluid Mechanics. Eighty percent of the students stated that these experiments increased their interest in their profession.

Despite the supportive opinions of the students, 56% of the students criticized the session period as being too short to complete the experiment. Based on their opinions, the four parts of the experiment will be divided into four separated sessions held on different days in the next semester.

8. Conclusions

In this paper, a study conducted by a graduate student to design and build an experimental set-up that would be used for undergraduate student education in one of the engineering laboratory courses has been presented. With this study, many educational objectives for the graduate student (who is also a graduate teaching assistant) and undergraduate students were fulfilled.

The graduate student has learnt both:

- how to design an experimental set-up, to conduct experiments with the set-up and to use the data obtained for fluid mechanics simulations (as an engineer); and
- how to conduct the experiments with the undergraduate students by preparing an experiment manual and oral exams, by conducting the experiments with the students and by grading the students' reports (as a GTA).

The undergraduate students attended the experimental sessions in the Spring semester of 2011, as planned. Each student prepared a report after the laboratory session. In this report, they had to obtain results from experimental data including the estimation of the uncertainties in measurements and discuss the results obtained with the related theory. All educational objectives were accomplished with both the laboratory session and the report preparation process. It can be concluded that the experiments facilitate the understanding of the theory by the students.

In conclusion, the impacts of the study on the undergraduate students and the graduate student, the designer of the set-up, are both remarkable. The constructed experimental set-up has been actively used in the department as a part of the laboratory course.

One important drawback of this study is the costliness of the education of the GTA. In order to teach the GTA how to teach, an experimental set-up was built and she was personally coached by her thesis advisor, while the responsibility of conducting the experiments was left to her. This, unfortunately, cannot be done for every single GTA. However, for a future faculty member, an educational study as described in this paper would be worthwhile.

As the final step of the study, the experiments were modelled with RELAP5/SCDAP MOD3.4 and the results of the simulation of the experiments and data were compared. The comparison of computational results and experimental observations will be presented in a separate study.

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