Session 3626

A FLUID MECHANICS LABORATORY NOZZLE DESIGN EXPERIENCE

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Abstract

As part of a four week fluid mechanics laboratory, students were challenged to design and manufacture the least restrictive flow nozzle for a standard test condition within several design constraints. The Nozzle Design Challenge (NDC) combined analysis, design, manufacturing, and experimentation. Each group of two students was given two acrylic rods of circular cross section from which individual flow nozzles were manufactured. Students were given preliminary nozzle design information contained in Fox and McDonald[1] and encouraged to obtain information from additional sources. The NDC was also a topic of discussion during the first few minutes of the lecture. The group's final nozzle design was based on previous experience obtained from the literature and analysis, and through experimentation. The entire design process and experimental results were detailed in the final laboratory report following the report writing format contained in Beer and McMurrey[2].

The positive student responses to the NDC were overwhelming. Formal evaluation of the results included the measured nozzle flow rates, amount of time spent in the laboratory, and the graded laboratory report. The highest flow rate nozzle allowed 210% more flow than the nozzle with a 1-inch diameter hole used for demonstration. Every group spent more time in the laboratory than was scheduled, indicating high levels of motivation for the project. However, the students did not perform as well on the laboratory reports, as indicated by low laboratory report grades. The authors suggest that there was not sufficient time provided to the students for the write-up, which contributed to the low report grades.

Introduction

In traditional fluid mechanics laboratory courses, students perform various experiments that highlight fundamental principles. UTEP, like many other institutions, has been investing in improving its laboratories. Many of the traditional experiments have been automated using computer data acquisition and control. Although the students, in general, have responded positively to the automated experiments, these experiments may require little to no active participation of the students, depending on the level of automation.

At UTEP, undergraduate fluid mechanics is a four credit hour course made up of three lecture and three laboratory hours each week. Mechanical, Industrial, and Civil Engineering students are required to take this course, yielding a fluid mechanics student population of widely varying backgrounds. The resulting fluid mechanics student population has significant differences in level of motivation for and interest in the study of fluid mechanics. In an attempt to involve the students in a more active laboratory experience and increase the level of motivation for the study of fluid mechanics, UTEP introduced a design experience as one of its fluid mechanics laboratories.

Students were challenged to design and manufacture the least restrictive flow nozzle for a standard test condition within several design constraints as part of a four week fluid mechanics laboratory. The Nozzle Design Challenge (NDC) combined analysis, design, manufacturing, and experimentation in the laboratory. The students were also required to document the design process and experimentation in a final laboratory report. The NDC was introduced for the first time in the Fall 1997 semester. In the following, the NDC is described and the results from that experience are detailed.

Description of the Nozzle Design Challenge

The Nozzle Design Challenge (NDC) was a four week laboratory session in which students were required to design, analyze, and manufacture the least restrictive flow nozzle. Groups of two students were formed and each group was provided two, 3-inch long and 3-inch diameter sections of acrylic rod, from which individual flow nozzles were manufactured. The nozzle was to be designed based on the principles of fluid mechanics within the following design constraints:

1. The original outer dimensions of the rod were to be maintained (*i.e.*, 3-inch outside diameter and 3-inch length).
2. The flow was to pass through a 1-inch diameter circular opening somewhere in the nozzle. A test bar was machined to 1.020-inch to ensure this requirement (*i.e.*, to meet the requirement, the test bar could not pass through the nozzle).
3. The maximum allowable circular diameter for the passage in the nozzle was 2.5-inch.

The students were given preliminary nozzle design information (*e.g.*, loss coefficients, pressure coefficients) contained in Fox and McDonald[1]. The groups were also encouraged to obtain additional information from additional sources, such as a formal library literature search, the internet, the instructor, the course textbook, additional faculty, and other fluid mechanics experts. Each laboratory session built on information “discovered” through experimentation and analysis from previous lab sessions. The first 5-10 minutes of the lecture period was also spent discussing relevant nozzle design information and answering questions. The group’s final nozzle design was based on previous experience obtained from the literature and analysis, and through experimentation. The entire design process and experimental results were detailed in a final laboratory report, and students were instructed to follow the formal report writing procedures outlined in Beer and McMurrey[2].

The maximum flow rate was determined by testing each nozzle on a test apparatus, called a flow bench. The flow bench is a standard measurement instrument that enables the user to control the pressure on the downstream side of the test piece. At the specified test pressure, the flow rate was measured using a calibrated orifice plate, located within the flow bench and downstream of the test piece. The test conditions used for the NDC were:

1. The test pressure on the downstream side of the nozzle was set at 25 inches of water (vacuum).

2. The upstream side of the nozzle was at atmospheric pressure (far away from the nozzle inlet).
3. All of the nozzles were clamped to the flow bench using the same procedure, and each test followed the same procedure.

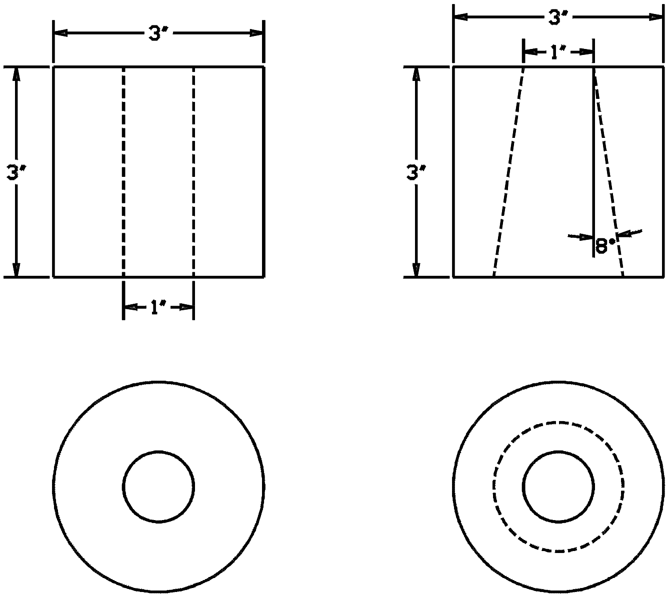
At the end of the four week session, students turned in their nozzles and final reports for grading. All of the nozzles were tested to determine the "official" flow rates for comparison. The grade for the laboratory was based on the formal laboratory report. However, for the NDC, there were bonus points given to the group with the highest volumetric flow rate (determined by at least 1% more flow than the next nozzle), and the best laboratory report (determined by the highest laboratory report grade). A maximum of 15 bonus points were available for the winner(s) of the NDC.

The student response to the NDC was remarkable. Every student demonstrated a motivation level not previously observed in the laboratory. Evidence of this was the comment made by the UTEP Machine Shop Specialist that he had never seen such a group of motivated students in the machine shop, and he has been at UTEP for 29 years. The following sections describe the events that occurred each week during the NDC, and have thus been subdivided into Weeks 1, 2, 3, and 4.

Week 1

During the first week of the laboratory, the students were introduced to flow measurement using the flow bench and general machine shop practices. Operation of the flow bench was demonstrated using the demonstration nozzles shown in Figure 1. Figure 1a represents a 1-inch diameter, 3-inch long orifice with sharp-edged entrance and exit. Figure 1b represents a 1-inch minimum diameter orifice with an 8-degree expansion angle (also with sharp-edged entrance and exit). The nozzle shown in Figure 1b can be used as an enlargement (diffuser) or contraction depending on the flow direction.

These simple nozzles demonstrated a number of important principles. For example, for the nozzle shown in Figure 1a, it was observed that the measured flow rate depended on the flow direction. The measured flow rate was 91.7 cubic feet per minute (cfm) in one direction and 92.5 cfm when the nozzle was inverted (this 1% difference was small but repeatable). An examination of the 1-inch hole revealed that the surface finish on one half of the hole was "smoother" than the other, indicating a different feed rate was used when machining the nozzle. The students were informed that the initially laminar boundary layer was "tripped" earlier in the "rough" direction, thus becoming a turbulent boundary layer sooner, increasing the pressure drop, and reducing the amount of flow through the nozzle. This explanation was consistent with the nozzle (*i.e.*, when the "rough" section was at the top, the measured flow rate was consistently lower than when the "smooth" section was at the top). This particular example highlighted some differences between turbulent and laminar boundary layers and the importance of the manufacturing process.



(a) (b)

Figure 1. Demonstration nozzles (a) 1-inch diameter hole, (b) 1-inch minimum diameter nozzle with 8-degree expansion angle.

The demonstration nozzle shown in Figure 1b had a measured flow rate of 102 cfm when tested as a contraction (flow from bottom to top in the figure), and 80.0 cfm when tested as a diffuser (flow from top to bottom in the figure). When tested as a diffuser, the flow was separating from the diffuser walls, thus creating large flow losses. These measurements provided the basis for discussions on the concept of pressure recovery and the complexity of diffuser design (during the NDC, the students quickly learned that a diffuser was necessary for their design to be competitive). Thus, with the help of the demonstration nozzles, the students were introduced to nozzle design basics, several flow phenomena, and the use of the flow bench for flow rate measurement.

After the demonstrations, the class was split into groups of four students and provided with a piece of acrylic rod to manufacture the nozzle shown in Figure 2. The Machine Shop Specialist discussed general safety issues and machine shop practices before allowing the students to machine the nozzle. The students spent between 2 and 2.5 hours machining their practice nozzle. Following the machining, the nozzles were tested on the flow bench.

At the end of Week 1 (there are four laboratory sessions to accommodate the number of students in the course), the flow rates for the different nozzles were compared. Even with the same nozzle design, the flow rates varied between 90 and 140 cfm, depending on surface finish, machining accuracy, and other things. From this exercise, the students recognized the practical difficulties encountered during the machining process and the benefit of pressure recovery to increase the flow rate for this particular flow situation. The wide variation in the flow rate among the different groups indicated that there was room for improvement with the nozzles. Thus, the groups spent Week 2 maximizing the flow rate through their nozzles.

Week 2

The second week was dedicated to maximizing the flow rate through the nozzles machined during Week 1 (see Figure 2). The students were encouraged to investigate how the flow rate could be increased by examining various loss coefficients and pressure coefficients provided in Fox and McDonald[1]. For example, entrance loss coefficients contained in Fox and McDonald[1] indicated a minimum loss coefficient, K, of 0.04 for an $r/D \geq 0.15$. The students then experimented with inlet radii to minimize the entrance losses. The students also experimented with the transition region between the 1-inch hole and the diffuser, making the transition rounded and smooth. The students discovered that a well designed venturi (a rounded inlet with a diffuser) would improve the flow rate. However, analysis and experimentation were required to determine the optimum design. The students explored the internet, performed literature searches and calculations, had discussions with faculty, students, and professionals to help identify their “optimum” design.

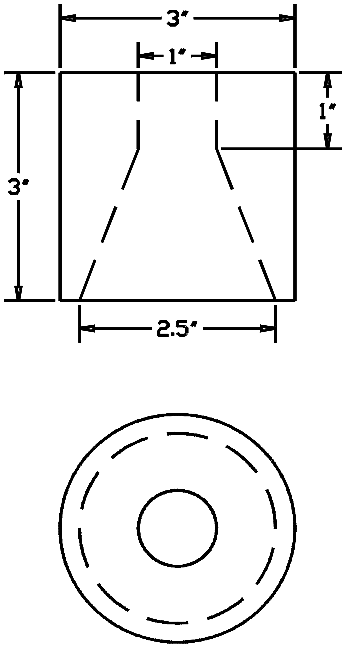


Figure 2. Nozzle design for group machining assignment.

Week 3

During Week 3, all of the nozzles from Week 2 were tested on the flow bench and ranked according to flow rate. These measurements are shown in Table 1. The nozzles were tested in both directions (*i.e.*, expansion and contraction). Numerous observations could be made of the results and the students were required to discuss the reasons for the wide variation in flow rates (~97 to 128 cfm) for the optimized nozzles.

Nozzle	a	b	c	d	e	f	g	h
Expansion	128	121	118	115	105	101	98	97
Contraction	106	106	110	113	105	103	107	103

Table 1. Measured flow rates (in cfm) of nozzles manufactured according to Figure 2 and optimized during Week 2.

In general, the groups attributed the widely varying flow rates to errors in machining, inaccuracies in the expansion angle (and thus flow separation), varying inlet radii, and varying degrees of surface finish. The responses can be summarized as follows:

1. The nozzle(s) with the highest flow rate had radiused edges, smooth inside surface, a smooth transition from the contraction to expansion, and did not contain any "gross" machining inaccuracies (such as steps, grooves, etc.).
2. The nozzle(s) with the lowest flow rate had sharp edges, sharp transition from contraction to expansion, and contained "gross" machining inaccuracies.

After Week 3, the students concluded that a venturi including a radiused inlet and a straight conical diffuser with polished surfaces was the most feasible design for maximum flow within practical machining constraints. However, the students had not experimented with optimum diffuser angle. The majority of the groups spent the remaining time experimenting with diffuser angle for this application. Again, Fox and McDonald[1] (and other sources) was referred to regarding pressure coefficients for straight conical diffusers.

Week 4

During Week 4, the individual groups were given two pieces of 3-inch diameter and 3-inch long acrylic rod for their final nozzle designs. The groups were active designing, machining, and testing their nozzles. Many techniques were investigated during the optimization of the individual nozzles. For example, some groups found that providing surface roughness helped ensure the flow remained attached to the nozzle in the expansion region. Other groups found the optimum diffuser angle by sequentially testing the measured flow rate in ~0.5 degree expansion angle increments. At the end of Week 4, the students were required to submit their final nozzle for testing and their laboratory report.

Results

The design of a "typical" nozzle submitted for the NDC is shown in Figure 3. Every group selected a venturi (or a radiused inlet with a straight conical diffuser) for their final design similar to the nozzle shown in Figure 3. However, the nozzles showed variations in inlet radius, expansion angle and length, surface roughness, and orifice diameter. Furthermore, some groups experienced difficulty machining accurately and thus, submitted nozzles with grooves, steps, and other machining inaccuracies.

Data collected for formal evaluation of the results included the measured flow rate, total machining time for each group, and the laboratory report grade. The variation of volumetric flow rate with respect to each group is shown in Figure 4. The data have been arranged from the maximum flow rate to the minimum flow rate. Also, the results for the demonstration nozzles (Figure 1) are included in Figure 4 for reference.

The winning nozzle had a flow rate of 189 cfm, representing a 210% improvement over the 1-inch diameter hole demonstration nozzle (~92 cfm). Fourteen of the nineteen groups designed nozzles with measured flow rates in excess of 150 cfm. The figure shows the different "levels" of flow

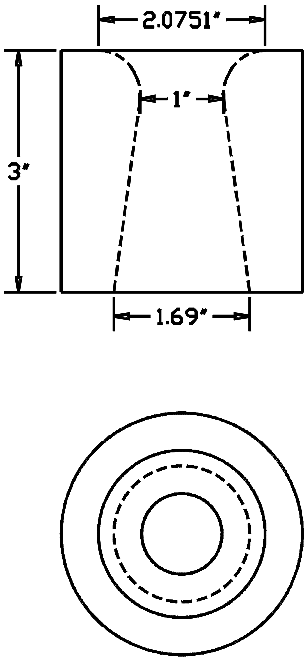


Figure 3. "Typical" nozzle design submitted for the NDC.

rate measurements between the nozzles. The average flow rate was 153 cfm, and the top three nozzles were separated by only 6 cfm.

Figure 5 shows the amount of time spent by each group in the machine shop. The groups spent between 7 and 10 hours in the machine shop during the NDC. However, it should be noted that some students had access to this and other machine shops, which is not reported here. All of the groups spent more time in the machine shop than the 4 hours and 50 minutes of machining time scheduled during the formal laboratory session for the final design. This indicates a high level of motivation for the NDC. The average reported machine shop time was approximately 8 hours (approximately 3 more hours than scheduled).

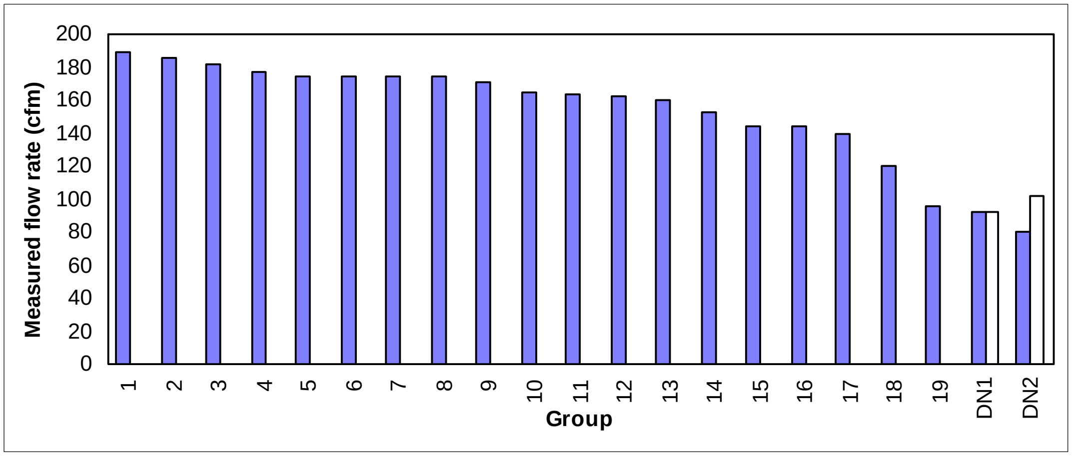


Figure 4. Measured flow rate at a test pressure of 25-inches of water for individual groups (DN1 and DN2 represent the demonstration nozzles shown in Figures 1a and 1b, respectively).

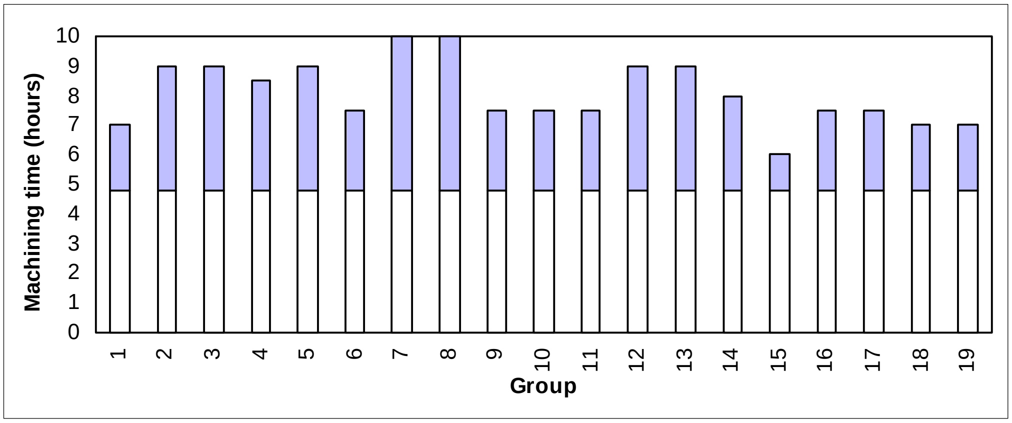


Figure 5. Total reported machining time for individual groups (4.83 hours of in-class laboratory time was available; shaded portion represents time spent outside of scheduled laboratory time).

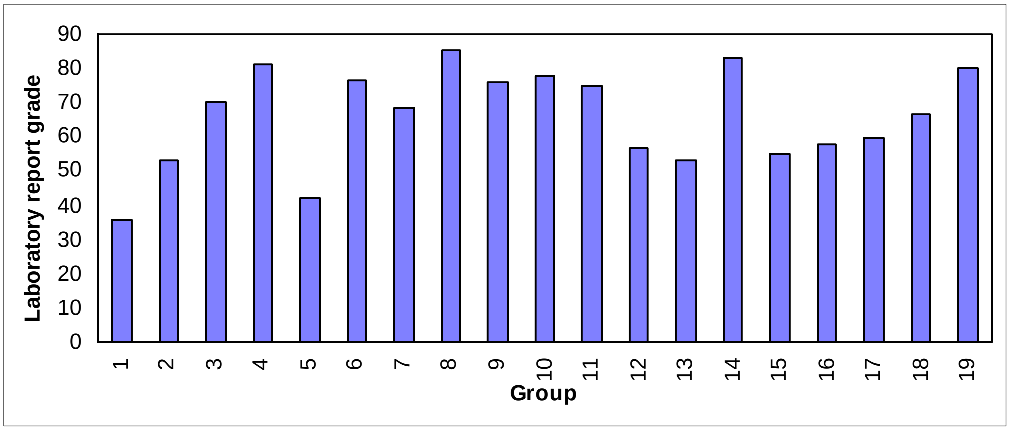


Figure 6. Laboratory report grade for individual groups.

Figure 6 shows the group laboratory report grades. The average laboratory report grade was 65.3, with only four groups scoring 80 or above. It is interesting that the apparent high level of motivation for the project does not appear in the laboratory report grades. Some possible explanations for this could be that the students were not as motivated to write their design results as manufacture their nozzle, the students were not provided adequate time to prepare their reports, the students were not prepared to write a formal laboratory report, and/or other explanations. In six previous laboratory sessions, the students had turned in reports and had become accustomed to writing formal lab reports. However, for the NDC, the reports and nozzles were both due the last day of the semester which undoubtedly affected student performance on the write-up. Thus, the authors conclude that the students were not provided adequate time to write their reports, which contributed to the low report grades. For future design challenges, more emphasis will be placed by the instructor on the report and the course will be structured so that sufficient time will be provided to the students for the write-up.

Several interesting points can be made when comparing Figures 4-6. The group with the highest report grade also spent the maximum time in the machine shop, indicating a high level of motivation for the entire laboratory. However, the team with the highest flow rate received the lowest report grade. This team also spent a below average amount of time in the machine shop. It appears that the winner of the design challenge experienced a certain amount of luck. Furthermore, the group with the lowest flow rate also spent a below average amount of time in the machine shop, but had an above average report grade. This particular group figured out that the emphasis of the laboratory was on the report grade and optimized their time accordingly.

Conclusions

At UTEP, an attempt has been made to more actively involve the students in the fluid mechanics laboratory. This was achieved by introducing the Nozzle Design Challenge (NDC), where over a four week period, students were challenged to design and manufacture the least restrictive flow nozzle for a given test condition and within several design constraints. The NDC combined analysis, design, manufacturing, and experimentation in the laboratory. Groups of two students were formed and each group was provided two, 3-inch long and 3-inch diameter sections of acrylic rod, from which individual flow nozzles were manufactured. The design process and experimentation were documented in a laboratory report.

The positive student responses to the design challenge were overwhelming. Formal evaluation of the results included the experimentally measured nozzle flow rate results, amount of time spent in the machine shop, and a graded laboratory report. The highest flow rate nozzle allowed 210% more flow than the nozzle with a 1-inch diameter hole used for demonstration. Every group spent more time in the laboratory than was scheduled, indicating high levels of motivation for the project. However, the laboratory report grades did not show the same level of motivation, and the authors suggest that there was not sufficient time provided to the students for the write-up.

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2. Beer and McMurrey (1997), A Guide to Writing as an Engineer, John Wiley & Sons, Inc., New York.

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