Session 2366

A Unique Leak Detection Precursor Capstone Design Project for a Hands-On Senior-Level Design Experience

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Abstract

This paper describes a design project for the senior level *Fluid and Thermal System Design* course, which is a precursor to the *Capstone Design Project* at Oakland University. The *Fluid and Thermal System Design* course is geared to taking students through the entire taxonomy of the design process; from knowledge, comprehension and application, to analysis, synthesis and finally evaluation. The leaktest design is the first design project of the course, and involves all of the aforementioned steps of the design process. The project is carried out during the first seven weeks of the semester, working in teams made up of three to four students, with one being the team leader. Results of the students' design experiences will be presented in this paper.

I. Introduction

The objective of the senior level Fluid and Thermal System Design course in the Mechanical Engineering program at Oakland University is to experientially nurture students in various aspects of the design process. The end result is the preparation of students to undertake the capstone design course. One of the major projects in this course is the design, implementation and experimental testing of a leak detection scheme for vacuum actuated control systems such as those found in the automotive industry.

Student teams, consisting of three to four students each, are design-engineering teams working for fictitious competing companies that specialize in custom testing solutions, and their implementation. A fictitious HVAC company is soliciting bids for the design of a testing scheme to save on labor time yet be accurate in validating their vacuum actuated control systems. Vacuum operated control systems are very common in the automotive industry. They are used in power brakes, automatic transmissions, disappearing headlights, and in climate control systems. Because they are mass-produced, the presence of leaks in these vacuum systems is inevitable. Therefore, there is a question as to how large a leak is tolerable. Once this is established, a manufacturing or quality control specification can be determined and the system checked on the assembly line. If it does not meet these specifications, then it must be pulled off the line and repaired.

The teams are to formulate a theoretical model that will provide insight into the physics of slow system leaks, which are distributed, in multiple unknown locations, throughout a vacuum actuated control system consisting of a vacuum reservoir, fittings, hoses and actuators. The best testing scheme will be that which will accurately test each system to meet certain quality control specifications for the product and be accomplished in a maximum time of 40 seconds. Along with a cover letter to the chemical company requesting the bid, each team submits a technical report documenting their company's proposed testing scheme. In addition, each team's design is verified in the laboratory that simulates a testing station.

II. Background of the Class Body

The *Fluid and Thermal System Design* class mainly consists of senior-level undergraduate students with a minority of graduate students. The course is a four-credit class, and involves both a lecture and a laboratory component. The lectures, however, do not introduce any new fundamental principles in the fluid and thermal sciences. Instead, the lectures serve to review and apply principles that have already been taught in introductory classes in thermodynamics, fluid mechanics and thermal energy transport. The laboratory component is strictly geared toward design, synthesis and evaluation, utilizing knowledge, and comprehension learned in previous courses.

The *Fluid and Thermal System Design* course was instituted in the 1970's to be the primary fluid and thermal design experience for graduating seniors. As a four-credit course, the class meets twice a week for approximately an hour and a half. The lectures consist of a variety of design-oriented applications. The lecture is broken up to include regular breakout sessions involving active learning techniques, student-centered learning and collaborative learning. Homework is assigned regularly to keep skills sharp and up-to-date.

The laboratory component is designed to nurture visualization and stimulate creativity. Rather than rely purely on simulation, the laboratory experience was made to be a hands-on experience. In fact, as part of the leak test design project, the student groups actually test their testing scheme prototype on an actual system, done the day the project is due. Many students appear to be initially intimidated by actual testing of their design, simply because they lack such experience. At the end of the course, however, these same students are typically the ones most proud of their accomplishment, and the most excited about their design experience.

III. Overview of Course Goals and Objectives

Oakland University catalogue course description:

> *"Study of systems involving fluid and thermal phenomena. Includes conventional and unconventional energy conversion, fluid and thermal transport. Analysis for the purpose of design and optimization of systems are emphasized using basic integral, differential and lumped-parameter modeling techniques. The course bridges conventional engineering design disciplines with design-oriented laboratory projects."*

The singular goal of the Fluid and Thermal System Design course is to expose students to, and challenge them to think about, the entire taxonomy of the design process. The lectures, including student-centered and active learning techniques, promote knowledge, comprehension and application. Regular homework and frequent small quizzes further promote these three important aspects of the design process. The hands-on laboratory design experiences then take students through the analysis, synthesis and evaluation. In this light, students get a global perspective of the design process.

Students are tested on all six elements in the taxonomy of the design process. The frequent homework and small quizzes test the students' knowledge, comprehension of the subject material as well as the ability to apply these aspects to solve engineering problems. The design projects then test the students' ability to analyze design problems, synthesize solutions and evaluate and therefore optimize the design.

IV. Design of a Testing Scheme; Quality Control Specifications

Following several lectures dedicated to thermodynamics and fluid and thermal principles, the design project is assigned to the student teams. Figure 1 is the initial specification sheet describing the design goals and quality control specifications. It should be noted that the graphs and equations, along with discussions, were exclusively taken from turned in student reports.

FLUID AND THERMAL SYSTEM DESIGN

ME 482/582 **C.J. Kobus**

DESIGN AND DEVELOPMENT OF A TECHNIQUE FOR AUTOMOTIVE ASSEMBLY LINE TESTING OF LEAKS IN VACUUM ACTUATED CONTROL SYSTEMS

Vacuum operated control systems are very common in the automotive industry. They are used in power brakes, automatic transmissions, disappearing headlights, and in climate control systems. Because they are mass-produced, the presence of leaks in these vacuum systems is inevitable. Therefore, there is a question as to how large a leak is tolerable. Once this is established, a manufacturing **or** quality control specification can be determined and the system checked on the assembly line. If it does not meet these specifications, then it must be pulled off the line and repaired.

Assume that you are a design engineer working in Automotive Climate Control, and you determine that the vacuum system associated with the Climate Control System could not tolerate leaks that would deplete the vacuum level, p_v, in the reservoir from 27 in Hg down to 2.0 Hg in less than 20.0 minutes at standard atmospheric conditions (29.92 in Hg and 59°F). This becomes a **quality control specification** on the integrity of the vacuum system.

Now, the testing must be done at a typical assembly line workstation that is 60 seconds duration. Allowing 20 seconds for hook-ups, system evacuation, and disconnect, the test itself must be completed in 40 seconds or less.

Design Specifications

Design and develop a testing scheme that in **40 seconds** will tell whether or not the vacuum system will meet the engineering **quality control specifications** stated above.

Figure 1: Initial project assignment and quality control specification

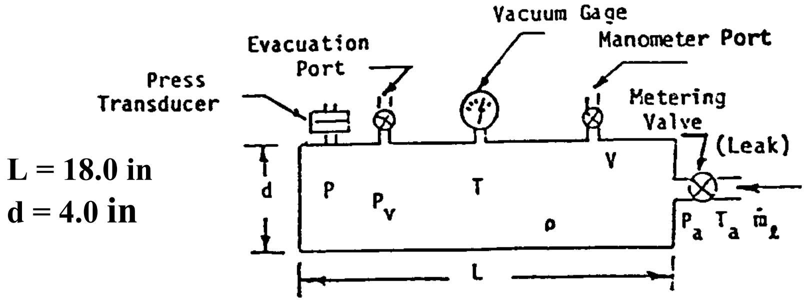
Since this may very well be the students first major design experience, this project is broken down into four separate pieces to help the student teams get started. Figure 2 is the specification sheet for the first of the four parts of the design project: to learn about the characteristics of vacuum actuated control systems with leaks being present.

FLUID AND THERMAL SYSTEM DESIGN

ME 482/582 **C.J. Kobus**

Design And Development Of A Technique For Automotive Assembly Line Testing Of Leaks In Vacuum Actuated Control Systems

PART 1: LEAK DETECTION AND MEASUREMENT



L = 18.0 in
d = 4.0 in

The aluminum tank represents the volume of a typical vacuum system and reservoir used in many engineering applications. An automobile has such a reservoir to provide a vacuum supply for operating the air distribution doors and valves associated with the climate control system. The presence of leaks in the system, which includes the reservoir, the hoses, and the vacuum motors, all of which are assembled on an assembly line, are inevitable. The purpose of this lab assignment is to investigate some aspects of the transient characteristics of vacuum system when leaks are present.

1. Use the experimental apparatus (Use both the mercury manometer and the pressure transducer to measure the vacuum level) provided to measure the vacuum ($p_v = p_a - p$; where p_a = atmospheric and p = absolute pressure), p_v, in Hg, and temperature, T, ^oF, as a function of time, t, see, when the metering valve, which is used to simulate a system leak, is set at a setting of 20.0 turns; starting at an initial vacuum level, $p_{v,i}$, at 27.0 Hg, and observing the decay down to 2.0 in Hg. Measure time at intervals of 1/2 in Hg vacuum. Measure barometric pressure, p_a, in Hg, and atmospheric temperature, T_a, ^oF. Repeat the above at 18.0 turns. (1 ½ page maximum)
2. Graph the vacuum level, p_v, as a function of time, t, for both sets of data. (1 page max)
3. Formulate a theoretical model for indirectly measuring the leak rate into the system, $\dot{m}_l$, in terms of known and/or measurable parameters and variables. (2 pages max)
4. Using the above model and the experimental data, determine (for both valve settings) the leak rate, $\dot{m}_l$, oz/hr, at vacuum levels, p_v, at every 1.0 in Hg from 27.0 down to 2.0 in Hg. Plot these results ($\dot{m}_l$, as a function of p_v). Discuss the results. (1 ½ page max)

Figure 2: First part of the design project; learning fundamental mechanisms of the leak

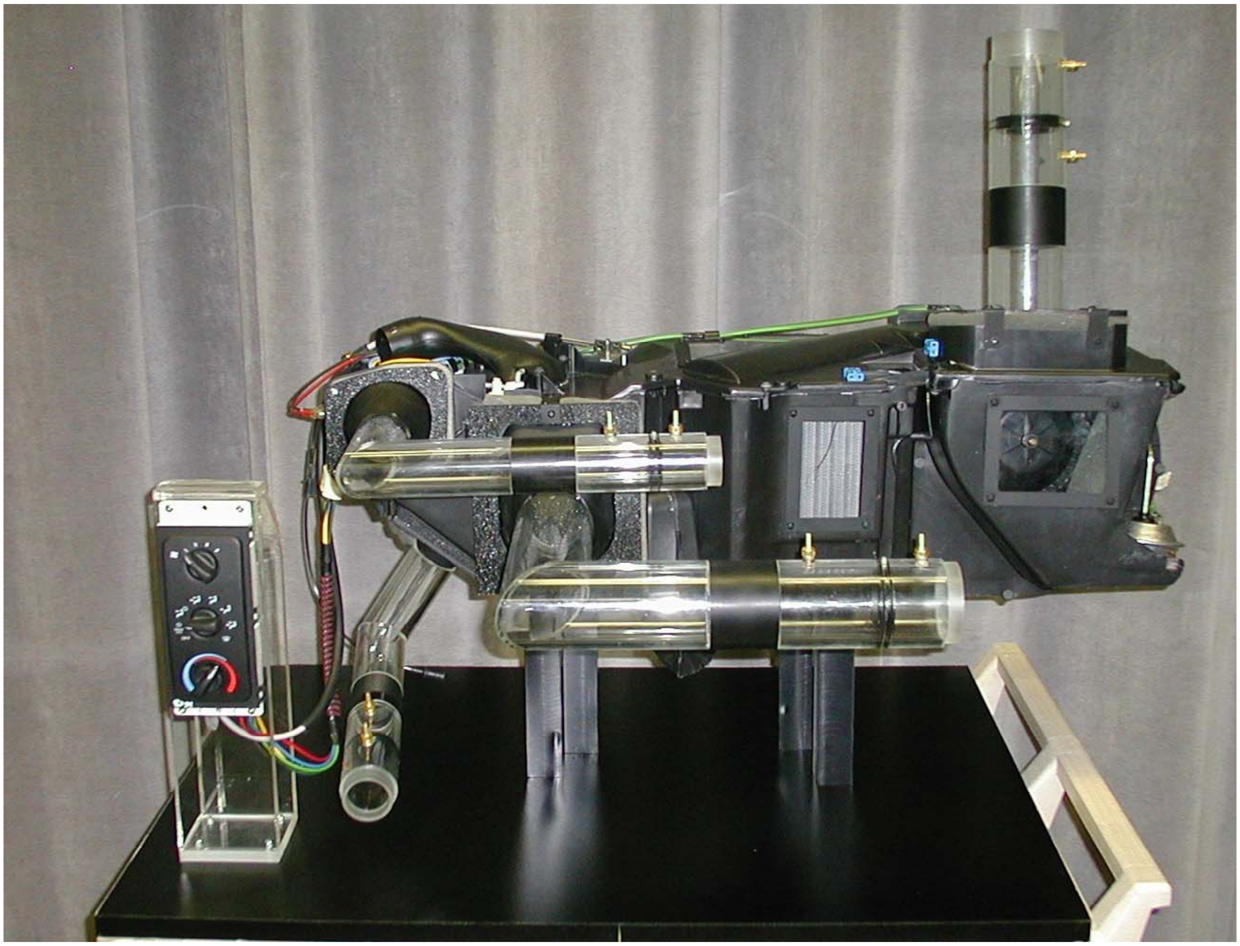


Figure 3: Automotive HVAC testing and demonstration apparatus

Prior to the experimentation, students are given a demonstration of an actual automotive vacuum-actuated system in an HVAC module, as illustrated in Figure 3. The various actuators for the registers, defrost, etc. are all dependent upon a reservoir with sufficient vacuum so that the pressure difference between it and the atmosphere is enough to trigger the various actuators. A lack of a significant vacuum will not allow the system to work properly.

The first portion of this laboratory involves the students in hands-on experimentation to gain insight into the physics of the leak. Figure 4 illustrates the gathered directly measured experimental data for two valve settings simulating different leak rates.

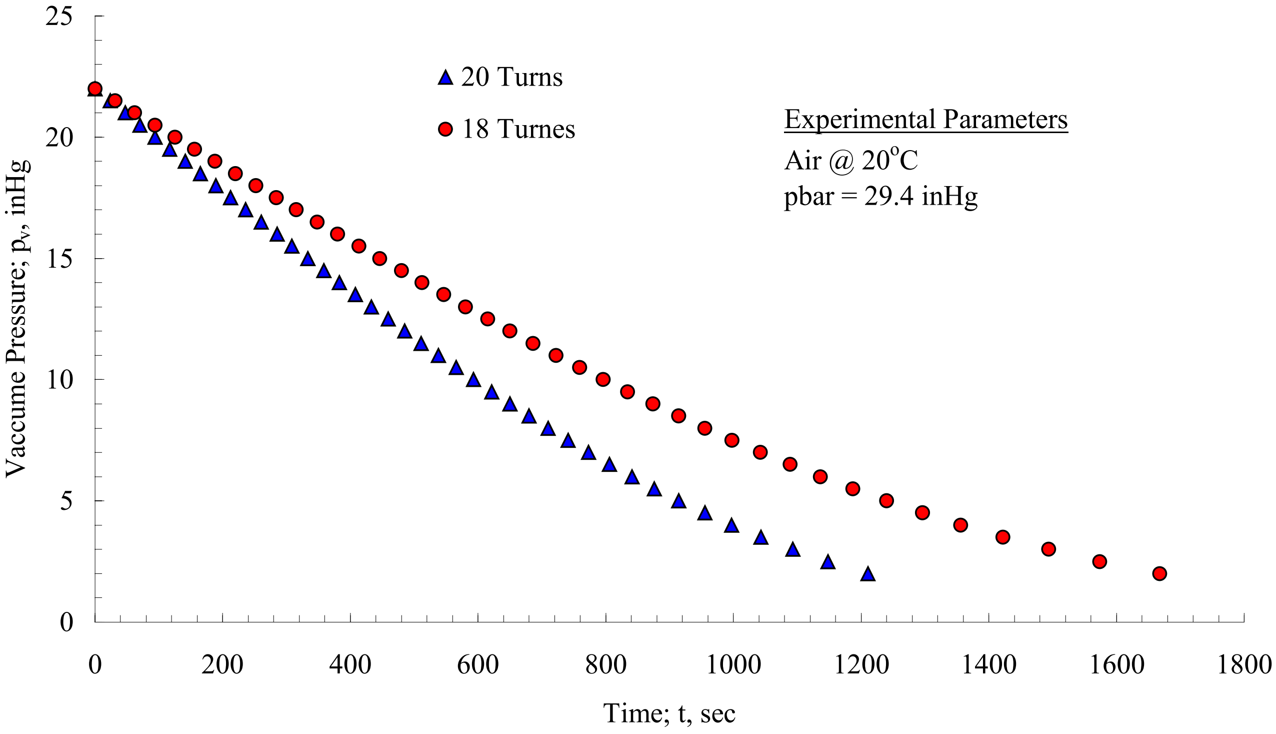


Figure 4: Directly measured experimental data of system vacuum level

For this experimental data to be viable, the student teams next must formulate a theoretical model for indirectly measuring the leakrate from the data. Thus,

Assumptions:

1. Properties are uniform throughout the volume
2. Ideal gas
3. Mass only enters the system, vacuum
4. Atmospheric temperature and atmospheric pressure are constants

Conservation of Mass:

$$\frac{dM}{dt} = \dot{m} \Rightarrow \frac{dM}{dt} = \dot{m}_i - \cancelto{0;(3)}{\dot{m}_o}$$

$$P_{abs} \forall = MRT \,;\, P_{abs} = P_{atm} - P_{vac} \Rightarrow -P_{vac} = P_{abs} - P_{atm}$$

$$\frac{d}{dt}(P_{abs} \forall / RT) = \dot{m}_l$$

$$(\forall / RT)\frac{dP_{abs}}{dt} = \dot{m}_l \,;\, T = \text{constant (from experiment)}$$

0;(4)

$$\frac{dP_{abs}}{dt} = \frac{d(P_{atm} - P_{vac})}{dt} = \frac{\cancel{dP_{atm}}}{dt} - \frac{dP_{vac}}{dt}$$

$$\therefore \dot{m}_l = -\left(\frac{\forall}{RT}\right)\frac{dP_{vac}}{dt} \qquad \text{Eq. (1)}$$

Unit conversions:

$$m_i = \frac{in^3}{\left(\frac{ft \times lbf \times \circ F}{lbm \times \circ R}\right)} \times \frac{inhg}{s} \Rightarrow \frac{in^3 \times lbm}{ft \times lbf} \times \frac{inhg}{s} \times \frac{lbf \times s^2}{32.2 lbm \times ft} \times \frac{ft^2}{144 in^2} \Rightarrow$$

$$\frac{in \times inhg \times s}{4636.8} \times \frac{3376.8 \frac{N}{m^2}}{inhg} \Rightarrow \frac{.7283 in \times s \times N}{m^2} \times \frac{m^2}{10.76 ft^2} \times \frac{ft^2}{144 in^2} \Rightarrow$$

$$\frac{4.7 \times 10^{-4} in \times s \times N}{in^2} \times \frac{lbf}{4.448 N} \Rightarrow 1.052 \times 10^{-4} \frac{lbf \times s}{in} \Rightarrow$$

$$1.052 \times 10^{-4} \frac{lbf \times s}{in} \times \frac{32.2 lbm \times ft}{lbf \times s^2} \times \frac{12 in}{ft} \Rightarrow .0408 \frac{lbm}{s} \times \frac{16 oz}{1 lbm} \Rightarrow$$

$$.653 \frac{oz}{s} \times \frac{3600 s}{hr} \Rightarrow 2352.5 \frac{oz}{hr} \text{ (Conversion factor)}$$

By utilizing Eq (1), the teams now may indirectly measure the leakrate, but first have to obtain an empirical relationship to determine the rate of change of vacuum pressure. The teams therefore have to obtain a best-fit curve of their experimental data, as illustrated in Figure 5. Following the obtaining of the empirical model, Eq. (1) may then be utilized to indirectly measure the leakrate, as demonstrated in Fig. 6.

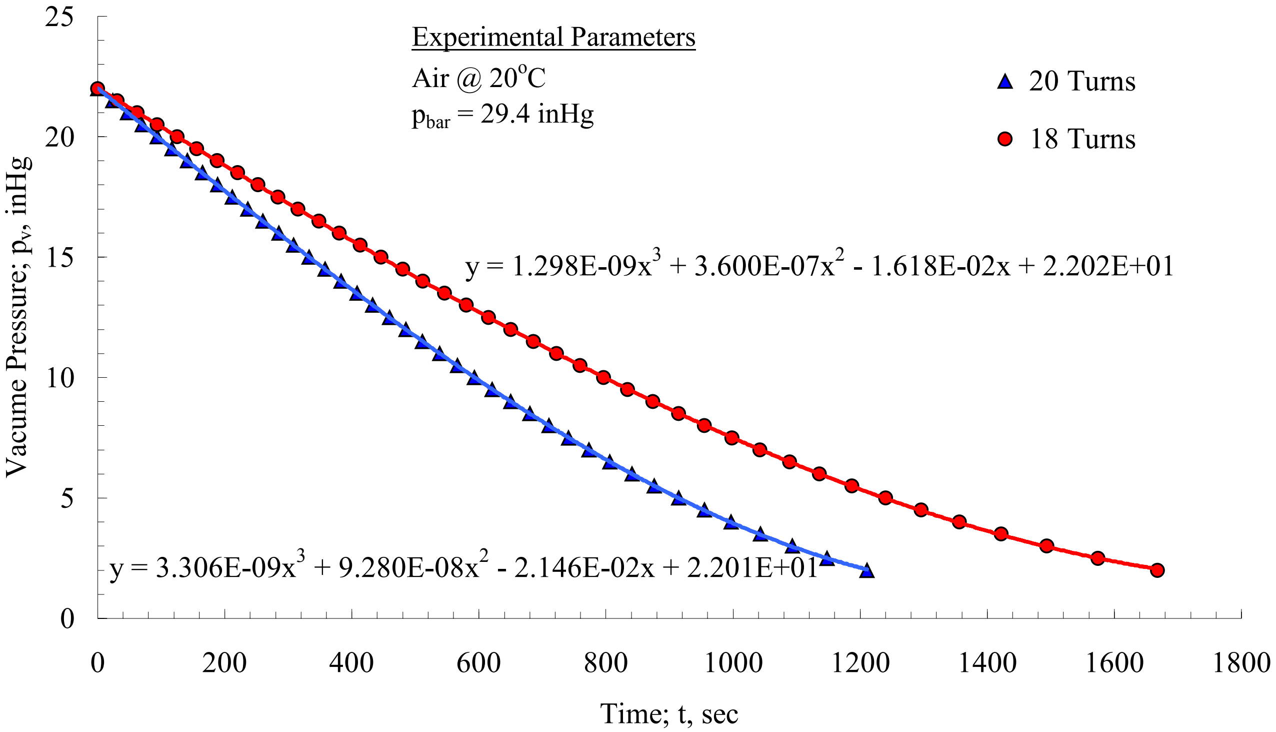


Figure 5: Empirical models for determining rate of vacuum decay

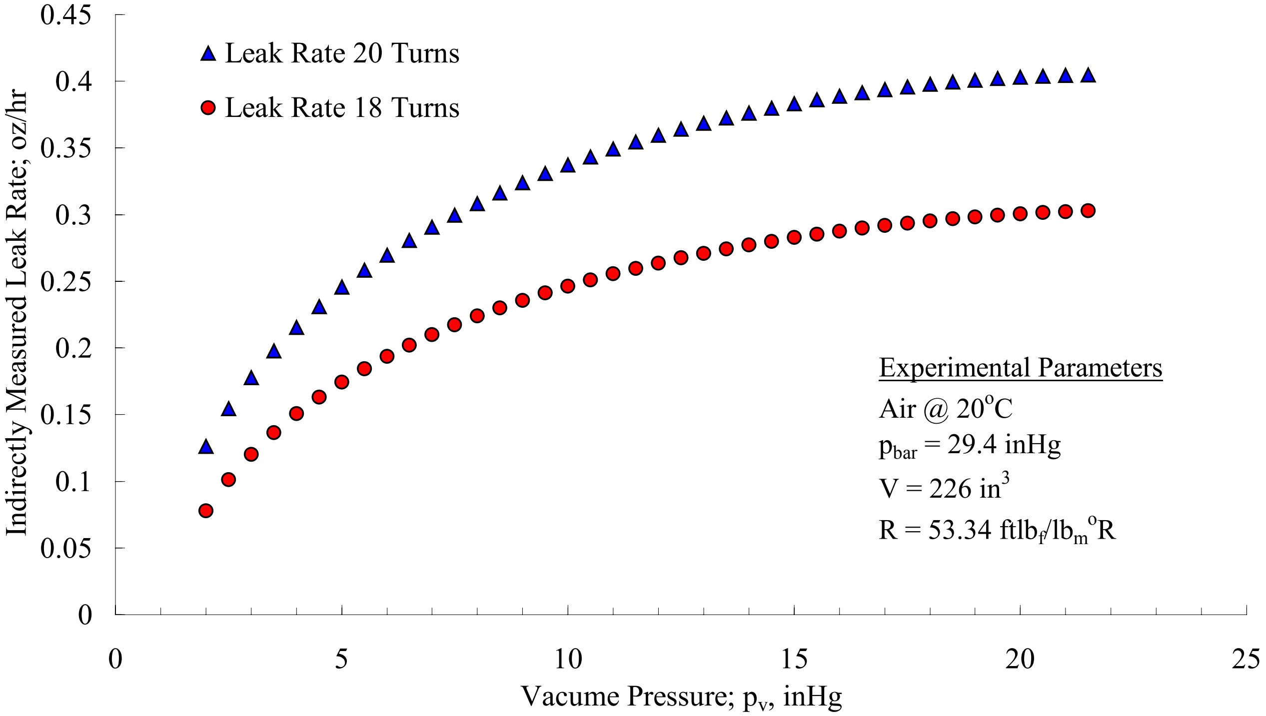


Figure 6: Indirectly measured leakrate for two different valve settings

FLUID AND THERMAL SYSTEM DESIGN

ME 482/582 **C.J. Kobus**

Design And Development Of A Technique For Automotive Assembly Line Testing Of Leaks In Vacuum Actuated Control Systems

PART 2: MODELING COMPRESSIBLE FLOW THROUGH A LEAK

The purpose of this assignment is the formulation of a theoretical model for predicting the flowrate of a gas through a leak as a function of the pressure drop across the leak.

1. Using the experimental data obtained in Lab Assignment #1, plot the indirectly measured leak rate, $\dot{m}_l$, as a function of the <u>absolute</u> pressure ratio, (p/p_a), for valve openings of 20.0 and 18.0 turns.
2. It is desirable to formulate an analytical model for the pressure drop across the leak, (p_a-p), in terms of the leak rate, $\dot{m}_l$. Consider the concept of an equivalent length, L_{eq}, for the leak like is normally done for viscous pressure drop in a pipe with incompressible flow. Expand on this approach with the concept of an equivalent diameter, d_{eq}, and flow area, A_{eq}, of the leak. Since the air is compressible, consider the Reynolds number and mass flow rate to be based upon the mean (arithmetic) value of the density, $\bar{\rho}$, of the air flowing through the leak.

   Show that the pressure drop across the leak can be expressed as:

   $$(p_a - p) = \frac{1}{2} f \left(\frac{L}{d}\right)_{eq} \frac{1}{\bar{\rho} A_{eq}^2} \dot{m}_l^2$$

3. Considering the air to behave like a perfect gas, the flow to be isothermal, fully developed and turbulent (Look at what happens to friction factor, f, on Moody diagram at high Reynold's numbers (especially for rough pipes), such that $f \neq f(Re_d)$, show that the leak rate, $\dot{m}_l$, can be expressed as:

   $$\dot{m}_l = c_f \left\{ \frac{p_a^2}{2RT}\left[1-\left(\frac{p}{p_a}\right)^2\right]\right\}^{1/2}$$

   where: c_f = flow coefficient; which is assumed to be constant with the dimension of area, is a function primarily of leak geometry, and can be determined experimentally.
4. Determine the flow coefficient, c_f, in^2, for valve openings of 20.0 and 18.0 turns, using the leak rate, $\dot{m}_l$, measured when the vacuum level, $p_{v,i}$, was equal to 27.0 in Hg.
5. Use the above experimentally determined flow coefficients, and the analytical model developed in #3 to predict the leak rate, $\dot{m}_l$, as a function of pressure ratio, (p/p_a). Superimpose (as solid lines) the above theoretical predictions of the model on the plot containing the two sets of experimental data developed in #1. Discuss the results.
6. Using the theoretical model for insight, explain what you feel are the physical mechanisms responsible for initially keeping the leak rate relatively constant even though the pressure drop across the leak decreases.

Figure 7: Second part of the design project; further modeling

The student teams, utilizing concepts from fluid mechanics, next derive a model for flow across a leak, in terms of some equivalent length (head loss) and diameter. It should be noted that there is no information on the geometry of the leak. In fact, the leak may be distributed in nature over the system. The concepts, however, are useful nonetheless.

$$f \equiv -\frac{dp'}{dz'} \Rightarrow p' = \frac{p}{\frac{1}{2}\rho v^2} \Rightarrow z' = \frac{z}{d} \Rightarrow f = -\frac{dp}{dz}\left(\frac{\rho v^2}{2d}\right)$$

Using this information, the pressure drop can be found as follows:

$$(p_i - p_o) = f\frac{\rho v^2}{2d}L_{eq} \Rightarrow f\frac{1}{2}\left(\frac{L_{eq}}{d_{eq}}\right)\rho v^2 \rightarrow \dot{m} = \rho v A \rightarrow v = \dot{m}/\rho A \rightarrow v^2 = \dot{m}^2/\rho^2 A^2$$

$$(p_i - p_o) = f\frac{1}{2}\left(\frac{L}{d}\right)_{eq}\frac{\rho\dot{m}^2}{\rho^2 A^2} \Rightarrow f\frac{1}{2}\left(\frac{L}{d}\right)_{eq}\frac{\dot{m}^2}{\bar{\rho} A^2_{eq}}$$

The following theoretical model was formulated with the assumption that the air behaves like a perfect gas, the flow was isothermal, fully developed, turbulent and the density was evaluated at average conditions; thus,

$$\bar{\rho} = \frac{\rho_a + \rho}{2} \Rightarrow \rho = \frac{p}{RT} \Rightarrow \frac{1}{2}\left(\frac{\rho_a + \rho}{RT}\right)$$

Therefore:

$$(p_a - p) = \frac{1}{2}f\left(\frac{L}{d}\right)_{eq}\frac{1}{\frac{1}{2}\left(\frac{p_a + p}{RT}\right)A^2_{eq}}\dot{m}^2 \Rightarrow \dot{m}_1^2 = \left(\frac{d}{L}\right)\frac{p_a - p}{f}\left(\frac{p_a + p}{RT}\right)A^2$$

$$\dot{m}_1^2 = \frac{d(P_a - P)(P_a + P)A^2}{fLRT} = \frac{d(P_a^2 - P^2)A^2}{fLRT} = \frac{dP_a^2\left(1 - \left(\frac{P}{P_a}\right)^2\right)A^2}{fLRT}$$

$$\dot{m}_1^2 = \left(\frac{d}{fL}\right)\left(\frac{P_a^2}{RT}\right)\left[1 - \left(\frac{P}{P_a}\right)^2\right]A^2 \Rightarrow \dot{m}_1^2 = \left\{\left(\frac{2dA^2}{fL}\right)\left(\frac{P_a^2}{2RT}\right)\left[1 - \left(\frac{P}{P_a}\right)^2\right]\right\}^{1/2}$$

$$c_f = \left(\frac{2d_{eq}A_{eq}^2}{fL_{eq}}\right)^{1/2} \Rightarrow \dot{m}_1 = c_f\left\{\frac{P_a^2}{2RT}\left(1 - \left(\frac{P}{P_a}\right)^2\right)\right\}^{1/2} \qquad \text{Eq. (2)}$$

Since the flow coefficient, c_f, cannot be obtained theoretically, because the leak geometry is unknown, it must be determined from experimental data. The flow coefficient, c_f, was found to be 5.09 $*10^{-5}$ in^2 for a valve opening of 18 turns and $6.81*10^{-5}$ in^2 for a valve opening of 20 turns. These values for the flow coefficient were found using a leak rate measured at vacuum pressure 27 in Hg. A comparison of this semi-empirical model and the experimental data is shown in Figure 8. The flow is thought to initially be constant because it is choked (sonic velocity). This would explain why the leakrate remains constant even though the pressure difference between the inside and outside of the system (which is the driving force for the leak in the first place) changes.

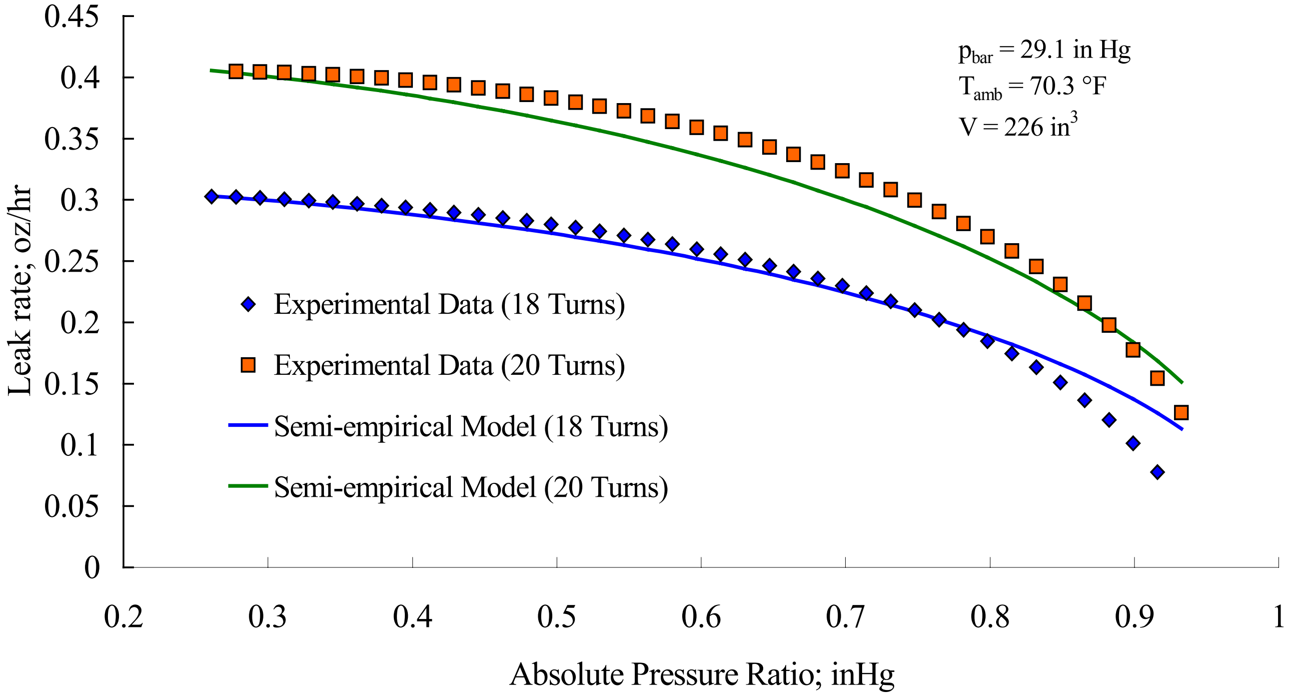


Figure 8: Indirectly measured leakrate for two different valve settings

FLUID AND THERMAL SYSTEM DESIGN

ME 482/582 **C.J. Kobus**

Design And Development Of A Technique For Automotive Assembly Line Testing Of Leaks In Vacuum Actuated Control Systems

PART 3: PREDICTING VACUUM DECAY TRANSIENTS

The purpose of this assignment is to develop an analytic model for theoretically predicting how the vacuum level in a vacuum reservoir that is subject to leaks varies with time.

1. Using the information developed in Labs 1 and 2, formulate a **differential equation** governing the absolute pressure, p, in the reservoir. Show that it can be expressed as:

$$\frac{dp}{dt} = c_f \left\{ \frac{RT}{2} \right\}^{1/2} \frac{p_a}{\forall} \left[1 - \left(\frac{p}{p_a}\right)^2 \right]^{1/2} \text{; where } c_f \text{ is the flow coefficient}$$

2. Show that the solution to the above differential equation satisfying the initial condition that

$$p_v(t)_{t=0} = p_{v,i}$$

can be expressed as:

$$p_v(t) = p_a - p_a \sin\left\{ \frac{c_f}{\forall} \left(\frac{RT}{2}\right)^{1/2} t + \sin^{-1}\left[1 - \left(\frac{p_{v,i}}{p_a}\right) \right] \right\} \text{; where } p_v(t) = p_a - p(t)$$

3. Superimpose the above theoretical prediction on a graph of your <u>original vacuum decay data</u>. Comment on the accuracy of the model's predictive capability.

Figure 9: Third part of the design project; modeling the leak

In this section of the design project, a differential equation for the pressure in the system is obtained by equating Eq. (1) from part#1 to Eq. (2) that was obtained in the previous assignment, both modeling the leakrate; thus,

$$\frac{\forall}{RT}\frac{dp}{dt} = c_f \sqrt{\frac{p_a^2}{2RT}\left(1 - \frac{p^2}{p_a^2}\right)}$$

$$\frac{dp}{dt} = c_f \left(\frac{RT}{2\forall}\right) \sqrt{\frac{p_a^2}{2RT}\left(1 - \frac{p^2}{p_a^2}\right)}$$

$$\frac{\mathrm{dp}}{\mathrm{dt}} = \mathrm{c_f}\left(\sqrt{\frac{\mathrm{RT}}{2}}\right)\frac{\mathrm{p_a}}{\forall}\sqrt{\left(1-\frac{\mathrm{p}^2}{\mathrm{p_a^2}}\right)} \qquad \text{Eq. (3)}$$

The differential equation found above was solved to derive the equation governing $p_v(t)$.

$$\frac{\mathrm{dp}}{\mathrm{dt}} = \mathrm{C_f}\left[\frac{\mathrm{RT}}{2}\right]^{1/2}\left(\frac{1}{\mathrm{V}}\right)\left[\mathrm{P_a} - (\mathrm{P})^2\right]^{1/2}$$

To simplify the constant β was defined:

$$\beta = \mathrm{C_f}\left[\frac{\mathrm{RT}}{2}\right]^{1/2}\left(\frac{1}{\mathrm{V}}\right)$$

Substituting β into the equation results in the following equation:

$$\frac{\mathrm{dp}}{\mathrm{dt}} = \beta\left[\mathrm{P_a} - \mathrm{P}^2\right]^{1/2}$$

Placing all of the p terms on one side and integrating both sides results in:

$$\int \frac{dp}{\left[P_a - P^2\right]^{1/2}} = \int \beta dt$$

Using integration tables from calculus p(t) was found:

$$\mathrm{p(t)} = \mathrm{p_a}(\sin(\beta \mathrm{t} + \mathrm{c})$$

where c is a constant of integration. The constant c was found to be $\sin^{-1}(1-\frac{P_{vi}}{P_a})$ by using the initial condition that the vacuum pressure at time t=0 is equal to the initial vacuum pressure; thus,

$$\mathrm{p(t)} = \mathrm{P_a}\left\{1 - \sin\left\{\mathrm{C_f}\left[\frac{\mathrm{RT}}{2}\right]^{1/2}\left(\frac{1}{\mathrm{V}}\right)\mathrm{t} + \sin^{-1}(1-\frac{\mathrm{p_{v,i}}}{\mathrm{p_a}})\right\}\right\} \qquad \text{Eq. (4)}$$

Referring to Figure 10, which compares the theoretical model of Eq. (1) with the original data, the trend of both experimental and theoretical vacuum pressure are closely related and follow the same trend. The slight deviations can be contributed to assumptions made when deriving our theoretical model. These assumptions are that the air behaved like a perfect gas, the flow is isothermal, fully developed and turbulent. It should be noted, however, that not only does our theoretical model predict very closely, but also it slightly overpredicts the leakrate, which has the advantage of being on the safe side of determining system failure.

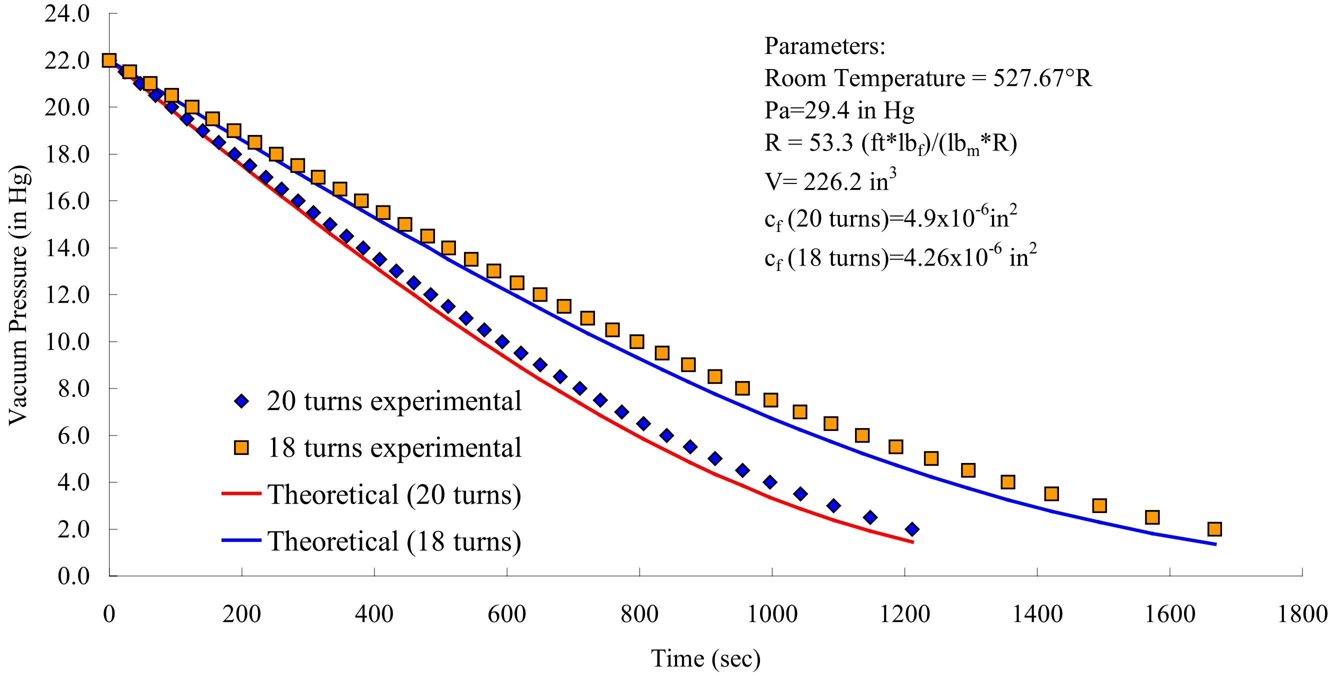


Figure 10: Comparison between theoretical model and original experimental data

Using the theoretical model developed in lab 3, the maximum allowable flow coefficient was calculated to meet the design specifications. The quality control specifications and the standard atmospheric condition were used in junction with the theoretical model at a specified time rate to develop the critical flow coefficient.

Standard atmospheric pressure: P_a=29.92 in Hg
Standard atmospheric temperature: 59˚F
Allowable vacuumed level drop: 27 in Hg to 2 in Hg in less than 20 minutes

Using the theoretical model:

$$P_v(t) = P_a - P_a \sin\left\{ \frac{C_{f,c}}{\forall} \left(\frac{RT}{2} \right)^{\frac{1}{2}} t + \sin^{-1}\left(1 - \frac{P_{v,i}}{P_a} \right) \right\}$$

Solving equation for $C_{f,c}$:

$$C_{f,c} = \frac{\forall}{\left(\frac{RT}{2} \right)^{1/2} t} \left\{ \sin^{-1}\left(1 - \frac{P_v(t)}{P_a} \right) - \sin^{-1}\left[1 - \frac{P_{v,i}}{P_a} \right] \right\} \qquad \text{Eq. (5)}$$

Using the given conditions in the quality control specification (Figure 1) the critical flow coefficient was found to be:

Parameters:

$T = 59°f = 518.67°R$ $\quad P_{v,i} = 26 \text{ in Hg}$ $\quad P(t) = 2 \text{ in Hg}$

$P_a = 29.92 \text{ in Hg}$ $\quad \forall = 226.2 \text{ in}^2$ $\quad t = 20 \min = 1200 \sec$

$$R = 53.33 \frac{ftlb_f}{lb_m °R} = 247434.134\left(\frac{in^2}{s^2 °R}\right)$$

$$C_{f,c} = \frac{226.2 in^3}{\left(\dfrac{247434.134\left(\dfrac{in^2}{s^2 °R}\right)518.67°R}{2}\right)^{1/2} 1200 \sec}\left\{\sin^{-1}\left(1 - \frac{2 inHg}{29.92 iHg}\right) - \sin^{-1}\left[1 - \frac{26 inHg}{29 inHg}\right]\right\}$$

Calculating the critical flow coefficient: $C_{f,c} = 2.5218 x 10^{-5} \text{ in}^2$

Using the critical flow coefficient calculated at the given quality control specifications; a model can be generated to directly test the system. This model will only be in terms of the different atmospheric conditions, pressure and temperature. Thus,

$$P_v(t) = P_a - P_a \sin\left\{\frac{C_{f,c}}{\forall}\left(\frac{RT}{2}\right)^{\frac{1}{2}} t + \sin^{-1}\left(1 - \frac{P_{v,i}}{P_a}\right)\right\} \qquad \text{Eq. (6)}$$

Parameters:

$P_{v,i} = 26 \text{ in Hg}$ $\quad \forall = 226.2 \text{ in}^2$ $\quad t = 40 \sec$

$R = 53.33 \frac{ftlb_f}{lb_m °R} = 247434.134\left(\frac{in^2}{s^2 °R}\right)$ $\quad C_{f,c} = 2.5218 \; E^{-5} in^2$

FLUID AND THERMAL SYSTEM DESIGN

ME 482/582 **C.J. Kobus**

Design And Development Of A Technique For Automotive Assembly Line Testing Of Leaks In Vacuum Actuated Control Systems

PART 4: PUTTING IT ALL TOGETHER

Vacuum operated control systems are very common in the automotive industry. They are used in power brakes, automatic transmissions, disappearing headlights, and in climate control systems. Because they are mass-produced, the presence of leaks in these vacuum systems is inevitable. Therefore, there is a question as to how large a leak is tolerable. Once this is established, a manufacturing or quality control specification can be determined and the system checked on the assembly line. If it does not meet these specifications, then it must be pulled off the line and repaired.

Assume that you are a design engineer working in Automotive Climate Control, and you determine that the vacuum system associated with the Climate Control System could not tolerate leaks that would deplete the vacuum level, p_v, in the reservoir from 26 in Hg down to 2.0 in Hg in less than 20.0 minutes at standard atmosphere conditions[1]. This becomes a quality control specification on the integrity of the vacuum system.

Now, the testing must be done at a typical assembly line workstation that is 60 seconds duration. Allowing 20 seconds for hook-ups, system evacuation, and disconnect, the test itself must be completed in 40 seconds or less.

Design Specifications

Design and develop a testing scheme which is 40 seconds will tell whether or not the vacuum system will meet the engineering quality control specification stated above. Your testing scheme must be designed such that the criteria for acceptable or unacceptable leaks are independent of the local atmospheric conditions where the cars are assembled. Stated another way, the same cars that pass or fail in Detroit on a hot day should also pass or fail in Denver on a cold day.

Assignment Specifications

1. The quality control specification is such that, at standard atmospheric conditions (29.92 in Hg and 59°F), vacuum leaks that allow the vacuum level in the system to drop from 27.0 in Hg down to 2.0 in Hg in less than 20.0 minutes cannot be tolerated. Determine the corresponding critical (maximum allowable) flow coefficient, $c_{f,c}$, in^2, that will meet this design specification.

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[1] 29.92 in Hg and 59°F

2. Be prepared to test several vacuum systems for leaks to see if they pass or fail to meet the design specifications. The test can only last 40 seconds, and will start at 27.0 in Hg. A computer controlled experimental data acquisition system will be used to monitor the vacuum level for the 40 second tests and determine the drop in vacuum level during that time. Be prepared to predict the <u>maximum</u> or critical 40 second **<u>vacuum level drop</u>**, $(Ap_v)_c$, that can be tolerated by the design specification at various extreme atmospheric conditions such as might be found in Rochester, Michigan and Denver, Colorado.

You will be given the atmospheric conditions (local barometer and temperature) and be given a maximum 5 minutes to predict the critical vacuum level drop, $(Ap_v)_c$, to be used in the actual testing scheme. Therefore, **<u>come prepared</u>**.

Outline of Formal Design Report[2] (Basic Elements)

Design and Development of a Technique for Automotive Assembly Line Testing of Leaks in Vacuum Actuated Control Systems

Cover Memo
One page memo written by your group leader from your (pseudo) company to your potential customer (that would be me), briefly describing your proposed assembly line testing technique, and your confidence in its capability to assure vacuum system quality control in the automobiles my company produces.

Abstract (Title page)

1. **Introduction** (Brief description of design problem quality control specifications and approach taken to develop a testing scheme)
2. **<u>Summary</u> of Theoretical Model Development**
    - 2.1) Indirect Measurement of Leakrate
    - 2.2) Theoretical Model for Predicting Leakrate; Comparison with Experimental Data
    - 2.3) Theoretical Model for Predicting Vacuum Decay; Comparison with Experimental Data
3. **Development of Assembly-Line Testing Technique**
    - 2.1) Utilization of Theoretical Model to Determine Critical Leak (Leak that just meets quality control specifications)
    - 2.2) Testing Scheme; Comparing actual leak with critical leak
    - 2.3) Utilization of Computer Controlled Experimental Data Acquisition System
        - Description
        - Results of Actual Leak Tests
4. **Conclusions**

Appendix (Copies of all hand out sheets for steps in design process)

Figure 10: Final part of the design project

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[2] This should be a separate, different report from the short intermediate or progress reports you have been handing in during the design process. Organization should follow above outline.

Thus, with conversion factors taken into account,

$$P_v(t) = P_a - P_a \sin\left\{ \frac{2.5218E^{-5} in^2}{226.2} \left(\frac{247434.134\left(\frac{in^2}{s^2 \,{}^\circ R}\right) T({}^\circ R)}{2} \right)^{\frac{1}{2}} 40\sec + \sin^{-1}\left(1 - \frac{26 inHg}{P_a}\right) \right\}$$

or,

$$P_v(t) = P_a - P_a \sin\left\{ .0015685(T)^{1/2} + \sin^{-1}\left(1 - \frac{26}{P_a}\right) \right\}$$

The next step in determining if the system meets the quality control specifications is to derive a critical vacuum **drop**, $(Ap_v)_c$. This theoretical critical vacuum level drop can now be determined for each testing phase and than compared to the computer simulated results. From the comparison of these two critical vacuum drops can be used to establish if the system meets the maximum leak rate.

Critical pressure drop in 40sec:

$$(Ap_v)_p = P_{v,i} - P(40\sec)$$

Once the critical vacuum drop was determined for a specific atmospheric condition (supplied by the instructor), a computer could measure the actual critical pressure drop in 40 sec. Table 1 below shows the results obtained in the computer controlled experimental data acquisition system at fixed parameter compared to the theoretical pass or fail criteria.

Table 1: Fixed parameters used in determining if the given system passed the control specifications for a given atmospheric condition.

Parameters:

Temperature (°F)	Barometric Pressure (in. Hg)	Volume of Tank (cu. in.)
70.89	29.23	226

Table 2: Test results from the computer controlled experimental data acquisition system compared to the theoretical prediction, resulting in a passed or failed system.

Test	Valve Opening (turns)	Allowed Pressure Drop (in. Hg)	Actual Pressure Drop (in. Hg)	Pass/Fail
1	29	1.05	1.37	Fail
2	7	1.05	0.81	Pass
3	17	1.05	1.2	Fail
4	11	1.05	0.96	Pass
5	14	1.05	0.99	Pass

Once a critical flow coefficient was calculated for 2 minutes the theoretical model could be used for any conditions because the *critical* flow coefficient is constant for all environments (cannot change the quality control spec). As long as the model used is a good one, it does not matter what the atmospheric pressure and temperatures are. This allowed us to calculate the critical pressure drop for a certain environmental setting for a 40 second test. If the system had a greater pressure drop than the theoretical model the system failed, and if it had a lesser pressure drop than the theoretical model it passed. A good operator could also tell if the system would pass or fail in 10 seconds by simply taking a quarter of the critical pressure drop found for 40 seconds and seeing if the system drops more or less.

V. Testing the Quality Control Specification

Figure 11 illustrates a Computer Aided Data Acquisition Analysis and Control System (CADAACS) that was utilized for the final test, done on the due date of the project. The system basically runs the entire leak test, from system evacuation to initiating the leak and comparing critical to actual pressure drops, outputting weather the system passes or fails. Controlling two solenoid valves, one leading to a vacuum pump, the other open to the atmosphere, does this. A pressure transducer monitors real-time vacuum level. In addition, real-time barometric pressure and temperature are monitored and changes in the critical vacuum level drop updated.

Figure 11: Computer Aided Data Acquisition Analysis and Control System (CADAACS)

When student teams come to the lab for their final test, the only information they get is atmospheric pressure and temperature. They must utilize their model from that point on to calculate the critical pressure drop under those conditions for the 40-second test. It should be noted that, at the instructor's discretion, any atmospheric conditions might be simulated, from Death Valley to the Himalayas. That is, conditions of the test can be changed without actually changing the atmospheric pressure and temperature in the room (which in turn can be quite uncomfortable should the instructor choose Death Valley to the Himalayas). Somewhat ironically, this is done by the instructor utilizing the model that is Eq. (6) to calculate a required *volume* for the wanted atmospheric conditions. If this volume is greater than the system volume (226 in^3), the additional volume can be attached to the system (the student teams do not know this and use 226 in^3 for all calculations). Should the required volume be smaller, filler to reduce the volume can be used (one such way is to partially fill the system with just the right volume of water or oil).

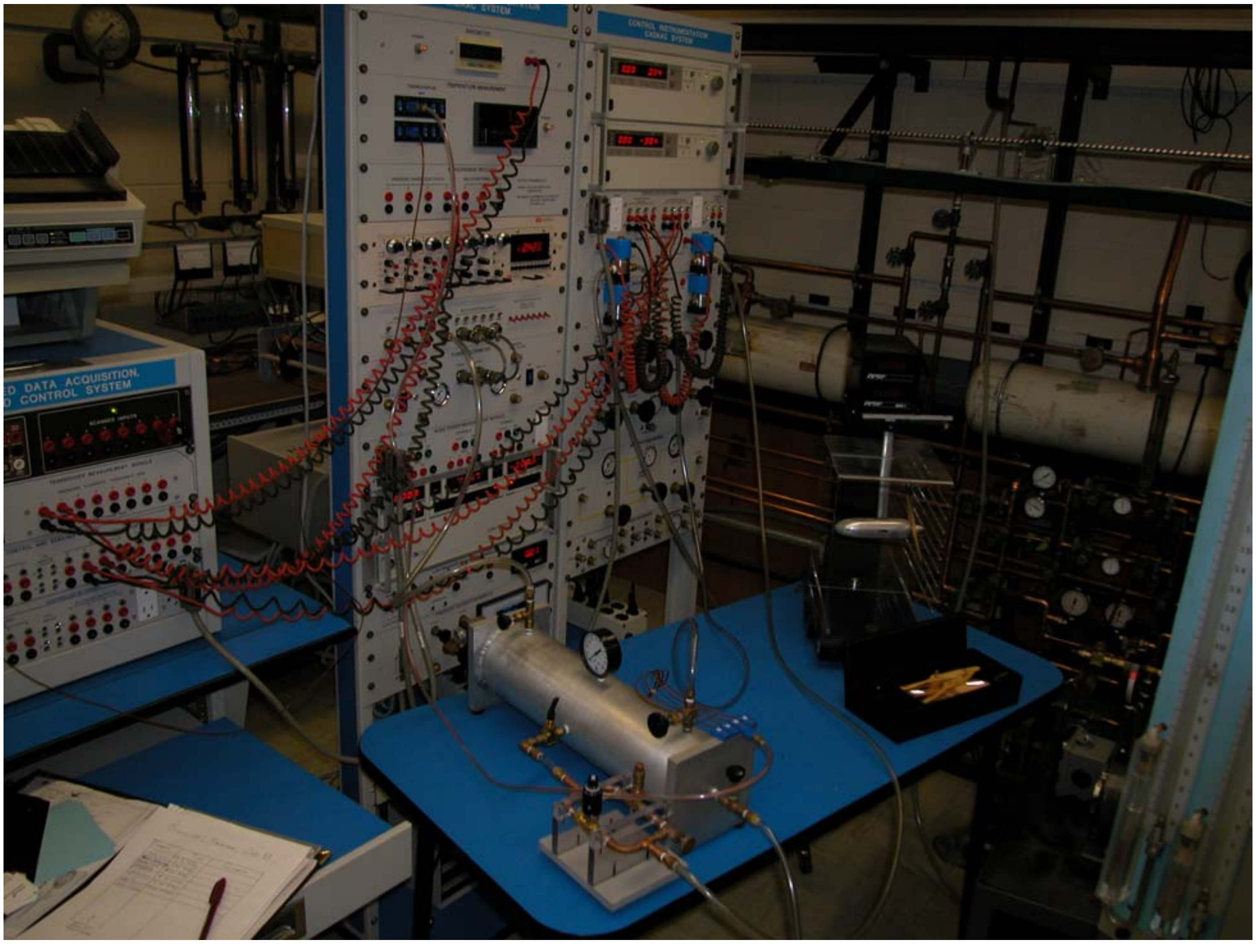

Figure 12: CADAACS system hook-up to aluminum tank

A total of five tests are performed. Once the team calculates the critical pressure drop (which is known to be correct or incorrect by the instructor), the CADAACS system is utilized to run the tests. Before each test, the metering valve (Figure 13) that dictates the size of the leak is altered by the instructor to preset values (which are known by the instructor to pass or fail). Since the test is run in a 40 second time span, and the vacuum level is displayed in real time, coupled with the instructor judiciously picking numbers in the quality control specification (Eq. 1) such that the critical pressure drop is always an even number (1 inHg, 2 in Hg, etc.), the teams are further challenged to predict pass or fail within the first 10 seconds by simply monitoring the vacuum level and their watch. This can only be done because the theoretical model, and previous data, indicates an initially constant leak rate into the system.

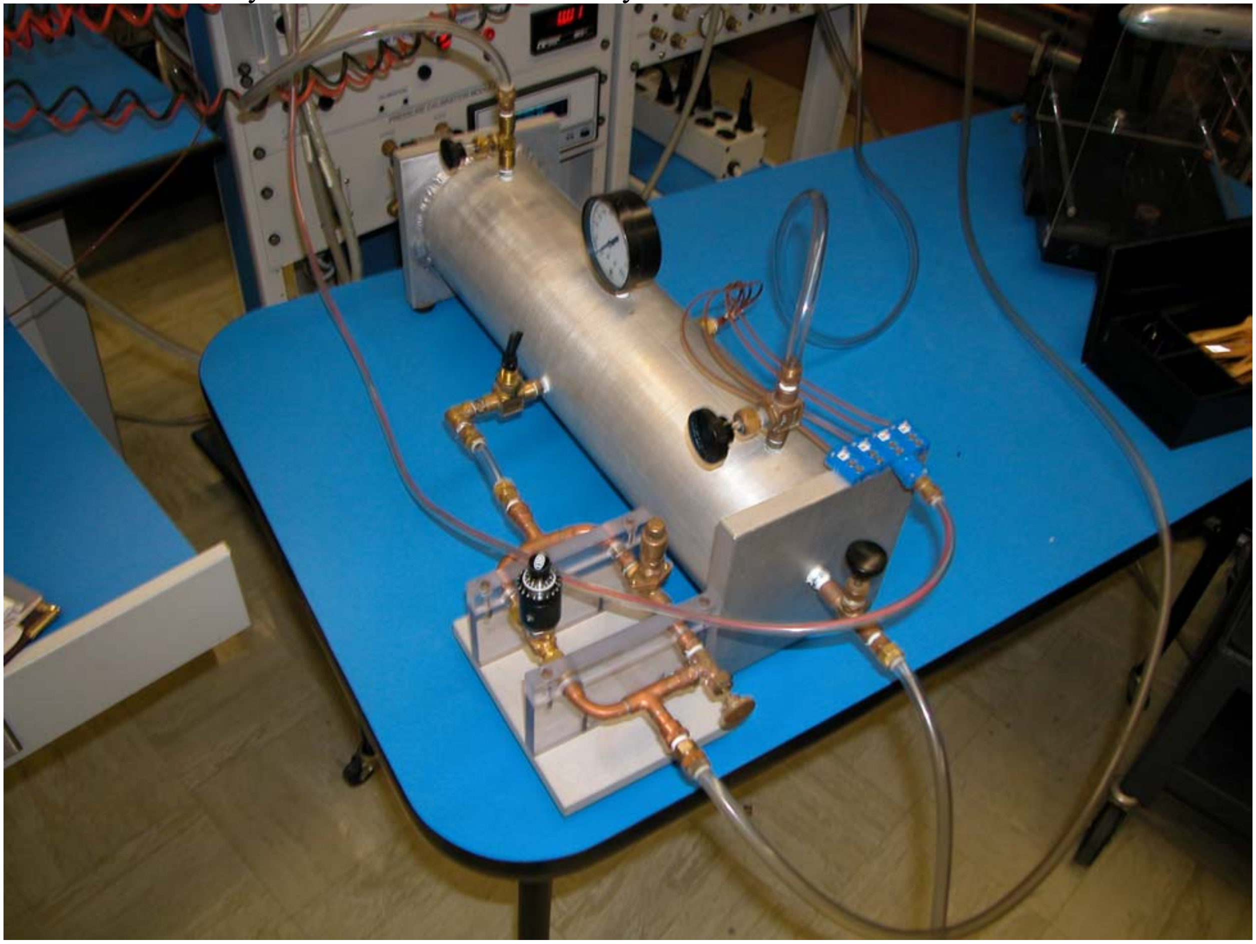

Figure 13: Close up of test system

Figure 14: The test!

VI. Results of Design Experience (What Students Learned)

This challenging and unique design project is intended to teach students fundamental values in a design process. Very early on (part 1), the value of simple modeling is reinforced, based on fundamental principles already taught in thermodynamics. In addition, utilizing empirical models to gather important information that could otherwise not be obtained is clear. Another aspect of this multi-stage design process is to teach that when confronted with a challenging problem, it is sometimes better to take small steps rather than tackling the totality of the problem immediately. Part 1 is a first step in which a simulation of a vacuum actuated control system (the aluminum tank) is experimented on to gain physical insight that will be useful later on in the design process.

Part 2 of the design process is the modeling of flow through a leak, even though the geometry of the leak is not known (in fact, leaks usually are distributed over the system). In spite of this fact, the concept of equivalent leak geometry (length, diameter, area, friction factor) is useful in employing knowledge from previous fluid mechanics courses to model the flow. The unknown parameters are then combined to form only one unknown parameter, which is called the flow coefficient. The only way to find this coefficient can be obtained is by again utilizing the available experimental data.

Part 3 of the design process was created to teach the value of good models in predicting physical phenomena. Without a good model, prediction of a critical flow coefficient and critical pressure drop cannot be done with any level of confidence.

VII. Student Feedback and Comments

Over the many years that this design project has been assigned, the student response has been very positive. During the course of the design project, I have had countless enthusiastic and excited design teams asking questions almost daily on modeling. Nearly every semester we see new ideas being generated by the teams.

This high level of enthusiasm invariably feeds back on the instructors, enhancing our own excitement for the project and for education in general. In turn, we continually work harder to refine our methods for education. Aside from the verbal enthusiasm, it is very apparent when the project write-ups are handed in that the design teams expended considerable energy toward the design project. In fact, the average grade for this particular project is generally higher than those associated with hands-on laboratory experiences in lower-level courses.

In addition, the final student course evaluations are unilaterally positive on their design experience in this course, and in particular this project. Although challenging, former students years later will visit and the projects in this course are an early topic of discussion.

VII. Summary and Conclusions

This paper provided a detailed description of a design project in the *Fluid and Thermal System Design* course offered to seniors at Oakland University. This course is intended to give students a global perspective of the design process, integrating the entire taxonomy from knowledge, comprehension and application to analysis, synthesis and finally evaluation. The leaktest project involves all of the aforementioned steps in the design process. The project is performed over the first seven weeks of the semester in teams of three to four students, with one student being the team leader.

Student groups are design-engineering teams working for fictitious competing companies that specialize in customized testing methods. The teams are to formulate a theoretical model that will provide insight into the phenomenon under consideration, taking into account both the overhead costs in testing time and the reliability based on quality control specifications. In addition to the responsibility for design, teams are provided with the ability to test the performance of the prototype testing scheme on an actual system with an unknown leak.

Judging from the variety of testing schemes, it is obvious that creativity had been stimulated by this design project. In addition, the many positive student comments on course evaluations, as well as unsolicited comments by the students, leads to the conclusion that this design project is not only valuable to the students' educations as engineers, but is a confidence builder as well.

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Bibliography

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