Experiments to Study the Gaseous Discharge and Filling of Vessels

J. CRAIG DUTTON AND ROBERT E. COVERDILL
Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

Two experiments are described that have been developed to demonstrate the fundamentals of unsteady, compressible flow. The experiments involve the discharge of gas from a pressurized vessel and the filling of an initially evacuated vessel. The hardware, software, and procedures for the experiments are summarized. In addition, theoretical solutions for the entire vessel filling and discharge process (choked and unchoked operation) are developed using both adiabatic and isothermal models of the processes. Example measurements from the discharge and filling experiments are presented and compared to the adiabatic and isothermal theories. The data are found to agree well with the theoretical predictions and follow the expected trends with respect to the rapidity of the processes.

AUTHOR QUESTIONNAIRE

1. The paper describes new training concepts in mechanical and aerospace engineering instrumentation.
2. The paper is useful in thermodynamics, fluid mechanics, or gas dynamics courses.
3. Level of students to be involved in the use of the equipment: junior or senior undergraduate students.
4. This paper highlights the development of analytical solutions, hardware, and data acquisition software to demonstrate the principles of unsteady, compressible flow.
5. The material presented can be incorporated in engineering teaching as a laboratory experience or classroom demonstration to be used in conjunction with thermodynamics, fluid mechanics, or gas dynamics lecture courses or a thermal science laboratory course.
6. The laboratory manuals cited as Refs. 1 and 5 in the paper provide additional support material; these manuals can be made available upon request.
7. The experiments have been used in the current format for the last five years. Student feedback on the experiments has been very positive.
8. These experiments can also be formulated as open-ended experimental design experiences. The analytical solutions are also useful in a number of practical engineering applications.

INTRODUCTION

EXPERIMENTS have been developed for the investigation of the discharge of compressed gas from a pressure vessel and the filling (charging) of an initially evacuated vessel. In each case the process occurs through a converging or converging-diverging nozzle. These experiments are used in a required senior-level course, 'Thermal Science Laboratory', in the mechanical engineering curriculum at the University of Illinois at Urbana-Champaign. This course is taken after completion of the introductory thermodynamics, fluid mechanics, and heat transfer lecture courses and demonstrates, in a laboratory environment, the theories and concepts developed in the classroom. In other curricular arrangements, the experiments described here may also be used effectively in conjunction with an undergraduate fluid mechanics or thermodynamics course or with a first course in gas dynamics.

One of the objectives of these laboratory exercises is to perform *unsteady*, *compressible flow* experiments, thereby providing a complement to the more usual steady, incompressible flow problems that an undergraduate student investigates. In this context the experiments provide the opportunity to reinforce several compressible flow concepts, particularly the phenomenon of choking and differences in operation between converging and converging-diverging nozzles. In addition, the use of a digital data acquisition system based on a personal computer using graphical object-oriented programming software, pressure transducers, and thermocouples simplifies the collection of data, provides rapid graphical representation of the data on the computer monitor, and demonstrates the power and utility of ordinary

desktop computers in a laboratory environment. The experiments are also relatively inexpensive to fabricate, and yield excellent, repeatable data that agree well with the theories developed for the vessel filling and discharge processes.

In addition to the usefulness of these experiments to engineering educators, the theoretical solutions that have been developed have found application in a variety of practical, industrial situations ranging from analysis of accident scenarios to prediction of the filling time of air bags and aircraft evacuation slides. We are unaware of any previous presentation of unified solutions for the entire vessel discharging or charging processes (i.e., both choked and unchoked operation). Such solutions, incorporating both adiabatic and isothermal models for the processes, are described briefly in the next section.

THEORETICAL DEVELOPMENT

Discharge analysis

The objectives of the analysis are to predict the pressure, temperature, and density of the gas in the tank and the mass flow rate out of the tank as functions of time during the discharge process. To accomplish these objectives the control volume shown in Fig. 1(a), which lies just inside the vessel walls, is used. In addition, the following assumptions are made:

1. Properties of the gas in the tank are spatially uniform at any instant of time (i.e., quasi-steady or uniform state assumption);
2. Average velocity of the gas in the tank is zero;
3. Opening modeled as an ideal converging or converging-diverging nozzle with isentropic flow to the nozzle throat;
4. One-dimensional flow and properties in the nozzle;
5. Neglect gravitational potential energy;
6. No shear or shaft work for the control volume;
7. Gas is thermally and calorically perfect;
8. Thermodynamic process is either adiabatic or isothermal.

The *adiabatic* assumption would be expected to be a good model for very rapid discharge processes in which case there would be little time for significant heat transfer between the tank walls and the gas. On the other hand, the *isothermal* assumption is expected to be appropriate for slow vessel discharge processes whereby there is sufficient time for heat transfer to maintain the temperature of the gas in the vessel constant.

Applying the integral continuity and energy equations to the control volume for the adiabatic case, the thermodynamic properties of the gas in the vessel can be shown to obey *isentropic* relations. In addition, for a large enough initial tank pressure P_i, compared to the back pressure P_B, the nozzle will be choked during the initial portion of the discharge process. By starting with the integral
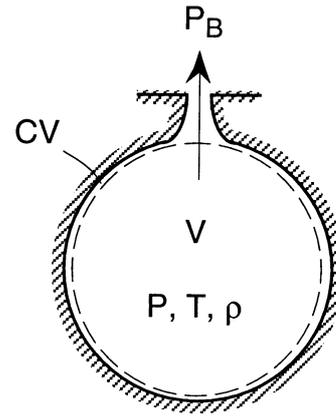
(a) Discharge
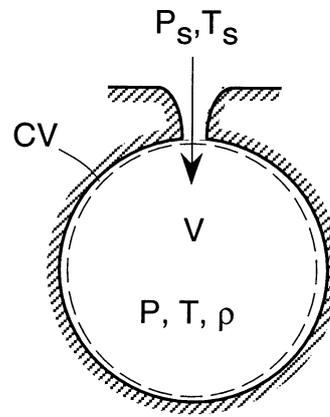
(b) Charge

Fig. 1. Control volumes used for the vessel discharge and filling analyses: (a) vessel discharge, (b) vessel charge.

continuity equation, substituting Fliegner's formula for the choked mass flow rate, and integrating the resulting ordinary differential equation, the solutions for the adiabatic and isothermal pressure/time histories in dimensionless form can be found as [1–3]:

Choked adiabatic solution:

$$P^+ = \left[1 + \left(\frac{\gamma - 1}{2} \right) \left(\frac{\gamma + 1}{2} \right)^{\frac{-(\gamma+1)}{2(\gamma-1)}} t^+ \right]^{\frac{-2\gamma}{(\gamma-1)}} \quad (1)$$

Choked isothermal solution:

$$P^+ = \exp\left[-\left(\frac{\gamma + 1}{2} \right)^{\frac{-(\gamma+1)}{2(\gamma-1)}} t^+ \right] \quad (2)$$

In the discharge analysis the gas thermodynamic properties are nondimensionalized with respect to their initial values so that $P^+ = P/P_i$ in the expressions above. In addition, the dimensionless time is defined as $t^+ = t/t_{\mathrm{char}}$ where the characteristic time is given by $t_{\mathrm{char}} = V/A_t a_i$. The symbols V,

A_t, and a_i denote the vessel volume, nozzle throat area, and speed of sound of the gas initially in the tank, respectively. In this dimensionless P^+-t^+ form, the pressure/time history of the gas in the vessel for both models is therefore dependent only on the single parameter γ, the gas specific heat ratio, as long as the nozzle is choked.

As the tank pressure falls toward the back pressure, the nozzle will eventually unchoke. The theoretical results can be extended through the unchoked regime by writing a mass flow expression at the nozzle exit plane, imposing the boundary condition that the nozzle exit static pressure must equal the ambient pressure, substituting this result into the integral continuity equation, and integrating the resulting ordinary differential equation using the unchoking point values (P^+_{unch}, t^+_{unch}) as the initial condition [1]. To our knowledge closed form solutions can only be obtained for t^+ as an explicit function of P^+, rather than vice versa, and only for cases in which the gas specific heat ratio is the ratio of integers, such as $\gamma = 7/5$ or $5/3$. A change of variables suggested by Owczarek [4] has been used in the unchoked analysis. The results for the adiabatic and isothermal model for $\gamma = 7/5$ are as follows:

Unchoked adiabatic solution:

$$t^+ = t^+_{unch} + \left(\frac{2}{\gamma-1}\right)^{1/2}\frac{A_t}{A_e}(P^+_B)^{\frac{-(\gamma-1)}{2\gamma}}$$
$$\times \left\{\left(\frac{x^3}{4}+\frac{5}{8}x\right)(x^2+1)^{1/2}\right.$$
$$\left.+\tfrac{3}{8}\ln\left[x+(x^2+1)^{1/2}\right]\right\}^{x_{unch}}_x \qquad (3)$$

Unchoked isothermal solution:

$$t^+ = t^+_{unch} + \left(\frac{2\gamma^2}{\gamma-1}\right)^{1/2}\frac{A_t}{A_e}$$
$$\times \left[\frac{(x^5_{unch}-x^5)}{5}+\frac{2(x^3_{unch}-x^3)}{3}+(x_{unch}-x)\right]$$

$$(4)$$

where

$$x = \left[\left(\frac{P^+}{P^+_B}\right)^{(\gamma-1)/\gamma}-1\right]^{1/2} \qquad (5)$$

The unchoked solutions are seen to depend on two additional parameters as compared to the choked solutions: the nozzle throat-to-exit area ratio A_t/A_e and the dimensionless back pressure $P^+_B = P_B/P_i$. Also, note that these solutions can be applied to the situation in which the entire vessel discharge is unchoked. In that case, equations (3)–(5) are used with P^+_{unch} replaced by unity and t^+_{unch} replaced by zero.

Charge analysis

The objectives, control volume, Fig. 1(b), assumptions, and solution methods for the vessel filling analysis are similar to those for the discharge analysis described above. For the adiabatic model, however, the relations among the thermodynamic properties are no longer isentropic. This result is consistent with the fact that the kinetic energy of the gas entering the tank must be dissipated if the average velocity in the tank is zero. In the tank charging analysis, the thermodynamic properties of the gas in the tank (whose initial values are P_i, ρ_i, and T_i) are normalized with respect to the constant source values P_s, ρ_s, and T_s, where atmosphere is used as the source and the tank is initially evacuated in the experiments described below. Thus, in the following expressions, the dimensionless pressure is defined as $P^+ = P/P_s$, and the dimensionless time is given by $t^+ = t/t_{char} = V/A_t a_s$ and a_s is the speed of sound in the source gas. The adiabatic and isothermal solutions for choked flow, which will occur if the initial tank pressure is low enough compared to the source pressure, are [2, 5]:

Choked adiabatic solution:

$$P^+ = P^+_i + \gamma\left(\frac{\gamma+1}{2}\right)^{\frac{-(\gamma+1)}{2(\gamma-1)}}t^+ \qquad (6)$$

Choked isothermal solution:

$$P^+ = P^+_i + T^+_i\left(\frac{\gamma+1}{2}\right)^{\frac{-(\gamma+1)}{2(\gamma-1)}}t^+ \qquad (7)$$

The adiabatic choked P^+-t^+ solution is seen to depend on the gas specific heat ratio γ and the initial pressure ratio $P^+_i = P_i/P_s$. The isothermal solution for choked flow depends on these two parameters plus the initial temperature ratio $T^+_i = T_i/T_s$. For both choked solutions the pressure increase with time is *linear*, but the rate of pressure increase for the isothermal case is smaller by the factor γ/T^+_i.

As the pressure in the vessel approaches the source pressure, the nozzle will unchoke and the expressions above can no longer be used. Adopting a procedure similar to that described previously for the unchoked discharge analysis, but now setting the nozzle exit static pressure equal to the tank pressure for the unchoked case, yields the following results for unchoked vessel filling [5]:

Unchoked adiabatic solution:

$$P^+ = \left\{1 - \left[(1-(P^+_{unch})^{(\gamma-1)/\gamma})^{1/2}\right.\right.$$
$$\left.\left.-\left(\frac{\gamma-1}{2}\right)^{1/2}\frac{A_e}{A_t}(t^+-t^+_{unch})\right]^2\right\}^{\gamma/(\gamma-1)} \qquad (8)$$

Unchoked isothermal solution:

$$P^+ = \left\{1 - \left[(1-(P^+_{unch})^{(\gamma-1)/\gamma})^{1/2}\right.\right.$$
$$\left.\left.-\left(\frac{\gamma-1}{2\gamma^2}\right)^{1/2}T^+_i\frac{A_e}{A_t}(t^+-t^+_{unch})\right]^2\right\}^{\gamma/(\gamma-1)}$$

$$(9)$$

Note that the two unchoked solutions are identical except that the last term of the isothermal model is smaller than that for the adiabatic model by the factor γ/T_i^+, which is similar to the results for choked flow. The nozzle exit-to-throat area ratio is also introduced as an additional parameter in both unchoked solutions as compared to the choked flow results. It should be noted that if these solutions are continued beyond the time at which $P^+ = 1$, the mass flow will become negative (i.e., *out* of the tank) and the pressure will decrease again, which is obviously physically unrealistic. Thus, the solutions should be terminated at $P^+ = 1$. As was the case for the discharge analysis, the solutions given above can be used for the situation in which the entire vessel filling process is unchoked. In that case, the equations for the unchoked regime are used with P_{unch}^+ replaced by P_i^+ and t_{unch}^+ replaced by zero.

In addition to the pressure/time history solutions presented above for the discharge and filling processes, similar time history expressions for the dimensionless density, temperature, and mass flow rate can also be developed from the thermodynamic relations that apply for the adiabatic and isothermal models. Further details about the theoretical analyses may be found in the laboratory manuals that have been developed for these experiments [1, 5]; these manuals are available from the authors upon request.

EXPERIMENTAL EQUIPMENT AND METHODS

Apparatus

A schematic diagram of the apparatus for the discharge experiment is shown in Fig. 2. Two separate vessels are available; the smaller one has a volume of $4920 \, \text{cm}^3$ while the larger tank has a volume of $29\,100 \, \text{cm}^3$. The vessels have several fittings, one each at the top and bottom and several on the sides. The lower and side ports are used, respectively, to mount a type T thermocouple, a pressure transducer (Sensotec 0–$1.4 \, \text{MPa(abs)}$ strain gauge-type), a connection for pressurizing the tank, and a pressure relief valve. The upper port is the location at which a nozzle, either converging or converging-diverging, is mounted, and through which the gas discharge occurs. As shown in Table 1, six nozzles are available, ranging from 1.63 to 6.36 mm in throat diameter. A small flange fastened with socket head screws holds the nozzle securely to its seat while an O-ring is used to seal the nozzle against the seat. A flat-faced plug with an O-ring that is attached to a
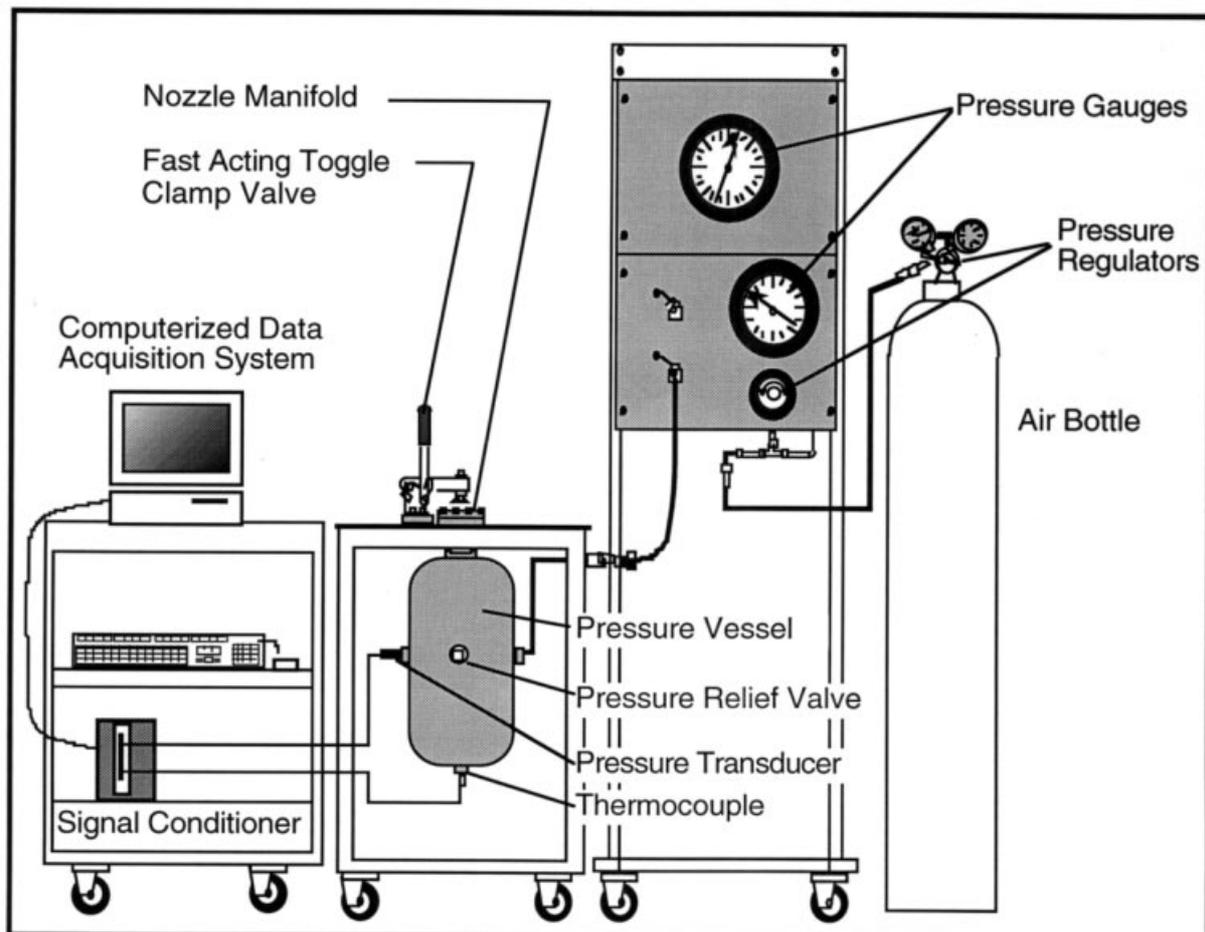

Fig. 2. Schematic diagram of the vessel discharge experimental apparatus.

Table 1. Nozzle dimensions and characteristic times

Nozzle No.	Description	Dimensions (mm)	t_{char} for $V = 4920\,\text{cm}^3$ (sec)*	t_{char} for $V = 29\,100\,\text{cm}^3$ (sec)*
QN1.1	Converging	$D_t = 1.63$	6.85	40.5
QN1.2	Converging	$D_t = 3.19$	1.79	10.6
QN1.3	Converging	$D_t = 4.79$	0.79	4.69
QN1.4	Converging	$D_t = 6.36$	0.45	2.66
QN2.1	Converging-Diverging	$D_t = 3.18$ $D_e = 4.11$	1.80	10.6
QN2.2	Converging-Diverging	$D_t = 4.78$ $D_e = 6.17$	0.80	4.71

* Assumes $T_i = T_s = 295\,\text{K}$ and that the gas is air.

fast-acting toggle clamp seals tightly against the outer face of the nozzle when it is placed in the closed position.

A standard bottle of compressed air equipped with a regulator is used to pressurize the test vessel. A second regulator on a calibration stand is used to adjust the initial pressure in the vessel. A flexible hose with a quick-disconnect type of fitting couples the calibration stand to the vessel. A three-way valve on the test vessel stand (not shown) is used to allow air to flow into the vessel during charging, and also to isolate the vessel from the calibration stand when charging is complete. The third position of the valve can be used to vent the gas in the vessel to atmosphere. The pressure in the vessel is displayed on a Bourdon tube gauge on the calibration stand and is monitored during vessel charging until the pressure has reached the desired initial value, typically around 1 MPa. Since the pressure data are nondimensionalized with respect to this initial value, the actual starting pressure used is unimportant, as long as it is sufficiently high that the nozzle will be choked initially (the usual case of interest). As stated above, a thermocouple is situated in each of the vessels to monitor the temperature of the air. However, the thermocouples have neither been sized nor located to follow the transient behavior of the discharge process; the thermocouple data are used primarily to determine the initial gas temperature. Once the vessel is pressurized, the temperature of the air in the tank is allowed to return to the ambient value before discharging it through the nozzle. Discharge of the vessel occurs when the fast-acting toggle clamp is actuated, removing the sealing plug from the face of the nozzle.

Instrumentation

A computerized data acquisition system that allows for rapid collection of pressure, temperature, and time data has been developed for this experiment. The system consists of an Apple Macintosh computer with 8 MB of RAM, an Apple color monitor, a data acquisition card (ours is a multipurpose card purchased from National Instruments, model NB-MIO-16H), and LabVIEW 2 software, also from National Instruments. The signals that are input to the A/D card are the voltage outputs from the pressure transducer and

the thermocouple that are located in the vessel. Since the time for complete discharge can last from a few seconds to several minutes depending on the vessel/nozzle combination being tested, the sampling interval of the LabVIEW application must be user selectable. This requires that the characteristic time t_{char} of the event be calculated, based on the tank and nozzle being investigated, to have a reasonably sized data set when completed (typically 50 data points are adequate). Since the A/D card is capable of greater than a 40 kHz sampling rate, this is an important step in the process. The sampling interval is entered in software from the 'front panel' of the 'virtual instrument' that is written in LabVIEW. A reproduction of the front panel for the discharge experiment is shown in Fig. 3. Displays of the pressure transducer output voltage and air temperature are included on the panel. In addition, the user may start, stop, or toggle between any of the three modes used to calibrate the transducer, monitor tank charging, or record data during the discharge.

After the process has ended, the data acquisition program is terminated and the raw voltage data from the pressure transducer are plotted versus time on the monitor by the LabVIEW program to verify that the event occurred properly (Fig. 3). The data are then saved to a spreadsheet file. Final data reduction is accomplished in a straightforward manner using the spreadsheet.

The apparatus and instrumentation for the vessel filling experiment are essentially identical to that described above for the discharge experiment. The only differences are that the compressed air bottle and calibration stand are replaced by a two-stage vacuum pump and a Bourdon type absolute pressure gauge to monitor the tank pressure, and 0–140 kPa(abs) Sensotec strain gauge pressure transducers are used instead of 0–1.4 MPa(abs) transducers. In addition, the nozzles are installed with their rounded entrance section facing *outward* (rather than into the tank as for the discharge experiment).

EXAMPLE RESULTS AND DISCUSSION

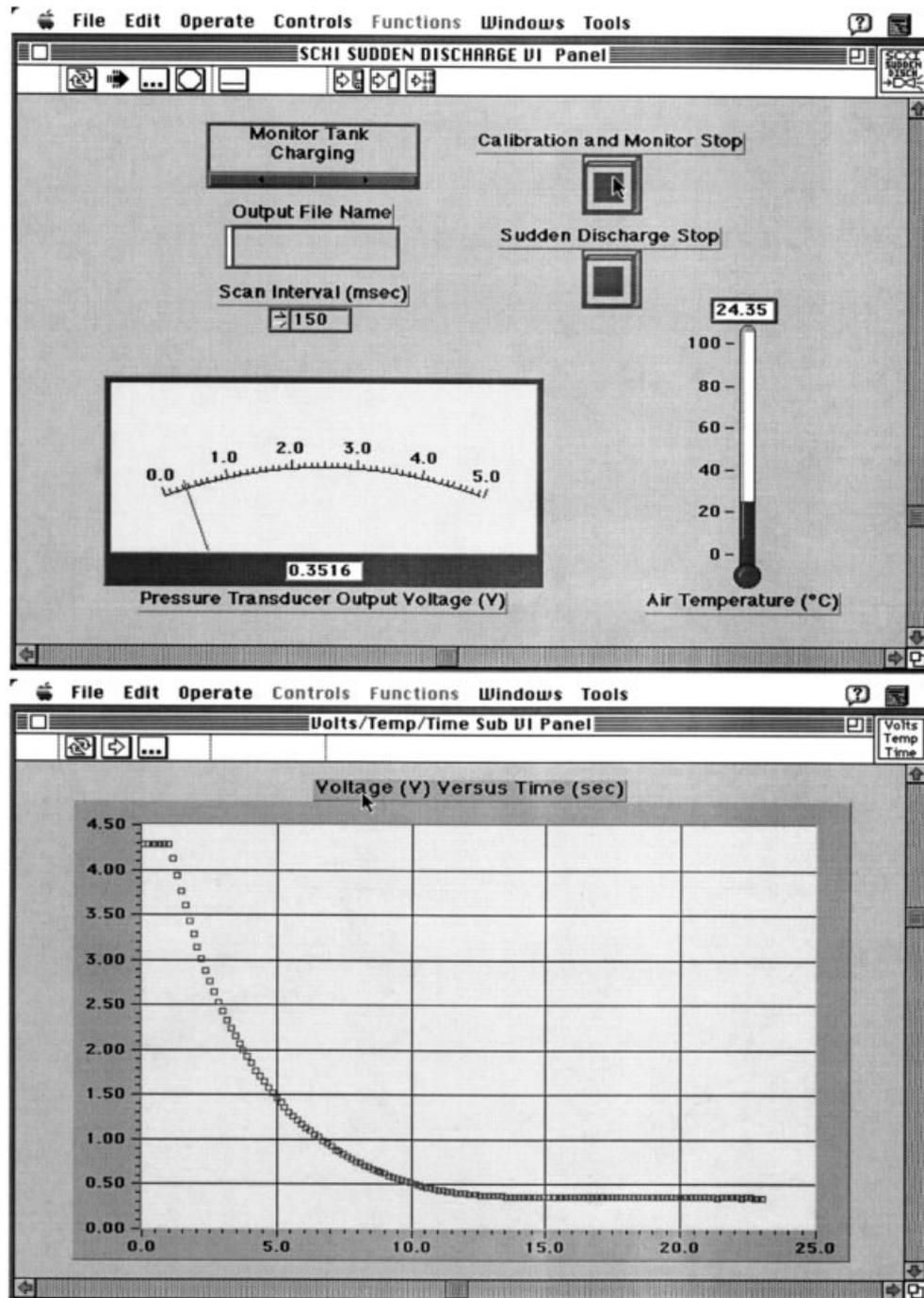Example measurements and comparisons to theory will now be presented for both the vessel

Fig. 3. Reproduction of the LabVIEW front panel for the discharge experiment.

discharge and filling experiments. In all cases experimental uncertainties are specified in the figure captions. These values have been determined using the uncertainty propagation procedure outlined by Coleman and Steele [6], together with the definitions of the plotted dimensionless variables: $P^+ = P/P_{ref}$ and $t^+ = (tA_t a_{ref})/V$. As discussed earlier, the reference conditions for the discharge experiment are the initial values of the gas in the tank, while for the charge problem they are the constant values of the source gas. Estimates of the bias and precision limits to 95% confidence have been made for each of the

component quantities in the definitions of the dimensionless quantities that are plotted.

Example vessel discharge results are shown in Fig. 4 where both the experimental data and the adiabatic and isothermal theories have been plotted. Figure 4(a) corresponds to the most rapid discharge possible with our hardware: the nozzle with the largest throat diameter mounted on the smaller tank (see Table 1 for nozzle dimensions and characteristic times). This discharge occurs in a little over 2 s (approximately five characteristic times), and the data are seen to agree well with the adiabatic theoretical results for the entire duration

(a) QN 1.4 – Small Tank
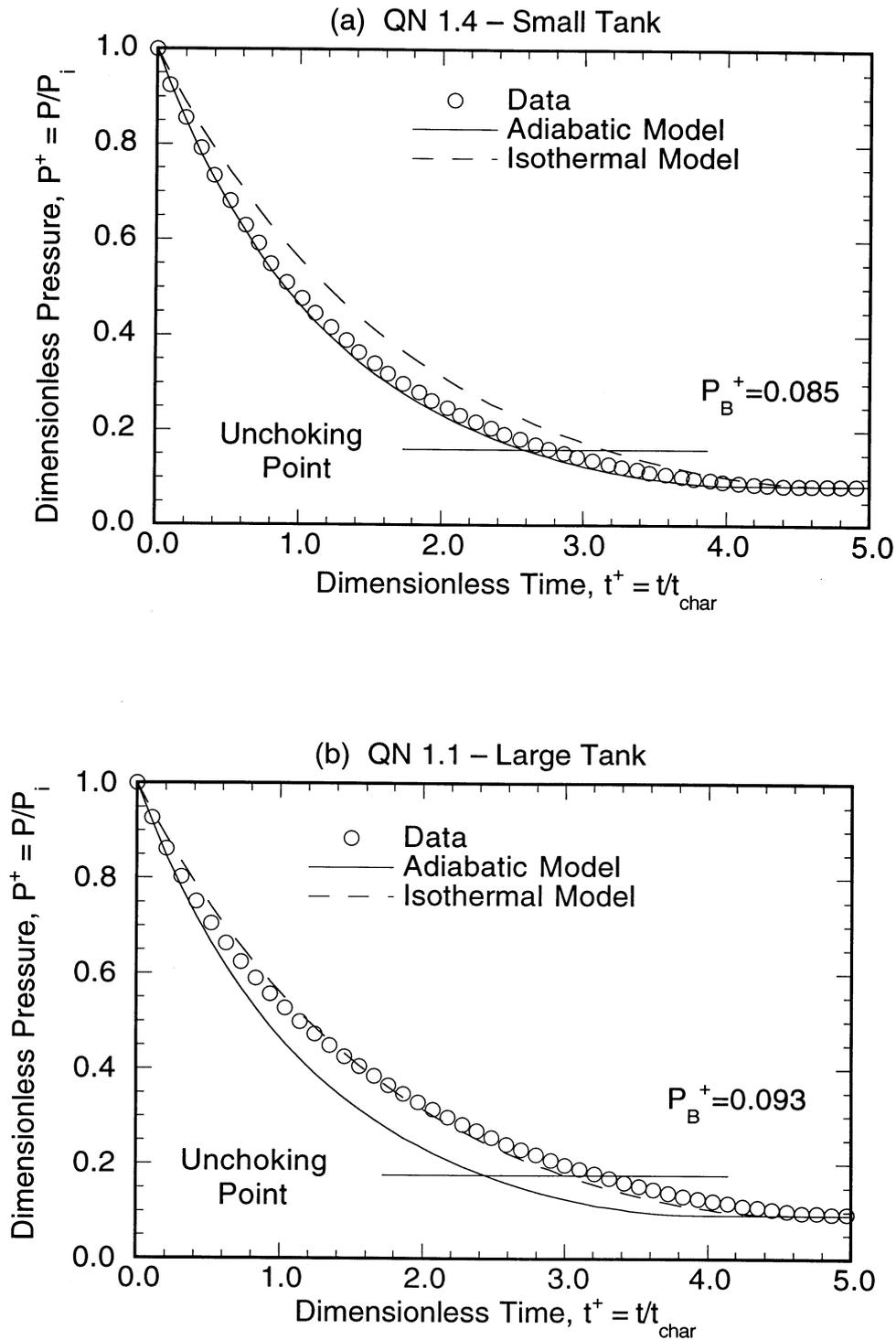

(b) QN 1.1 – Large Tank

Fig. 4. Example single experiment data for the discharge experiment: (a) nozzle QN1.4—small tank, (b) nozzle QN1.1—large tank; uncertainty in $P^+ = \pm0.0075$ and in $t^+ = \pm0.15$ to 95% confidence.

of the process. At the other extreme is the smallest throat diameter nozzle used in conjunction with the large tank, Fig. 4(b). In this case the process requires about 200 s. During the initial stages of the discharge, the data follow the adiabatic theory quite closely, as there is little time elapsed and only a small temperature difference between the gas and vessel walls, so that significant heat transfer does not occur. However, as the discharge proceeds,

heat transfer does occur, the gas tends to remain at constant temperature, and the P^+-t^+ results more closely follow the isothermal theory. The thermocouple measurements, which are admittedly qualitative for the reasons discussed above, agree with this reasoning.

Figure 5 presents composite results for two series of experiments that can be performed with this hardware. In Fig. 5(a) the initial tank pressure,
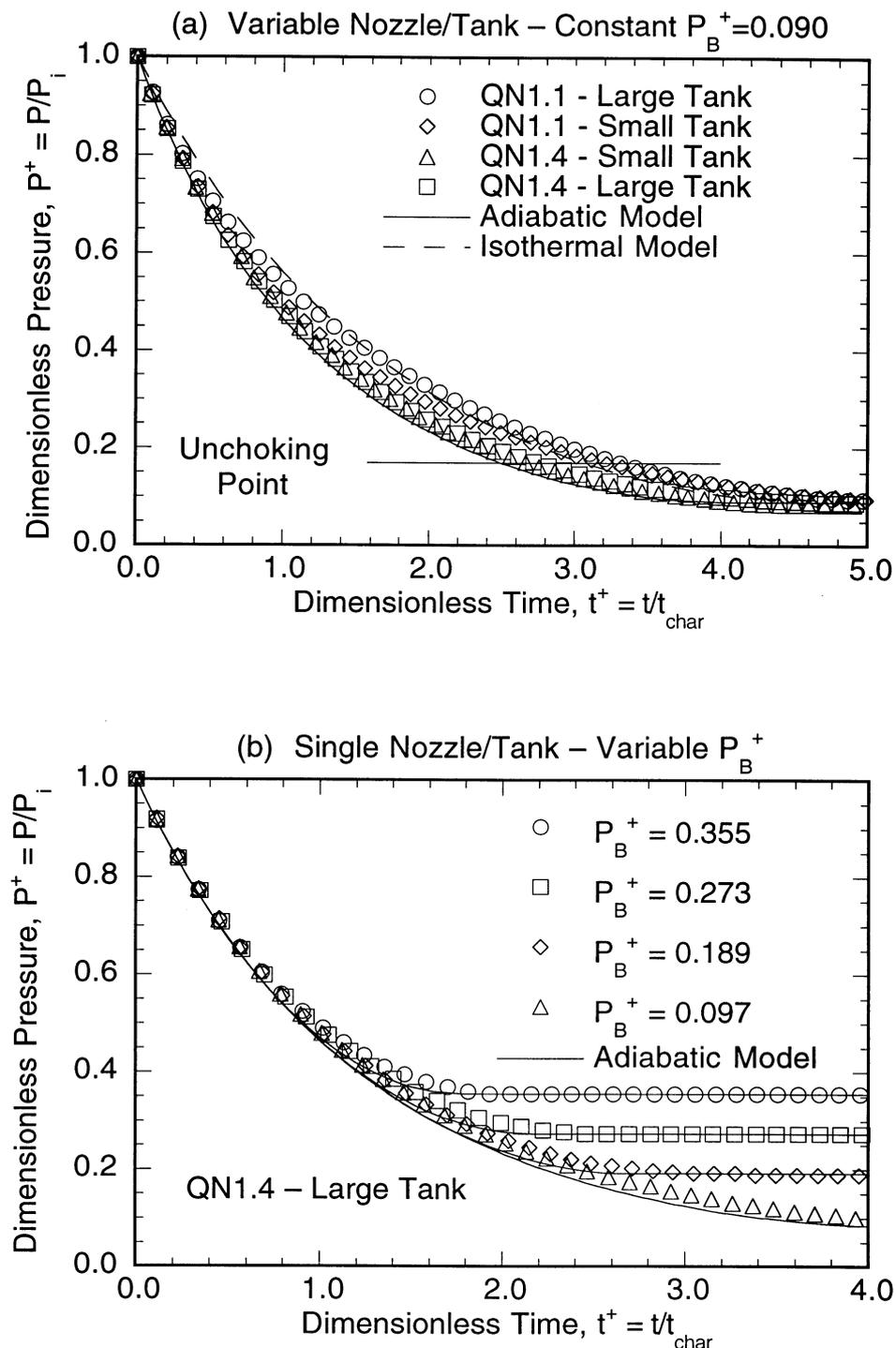
Fig. 5. Example composite data for the discharge experiment: (a) variable nozzle-tank combinations and constant P_B^+, (b) variable P_B^+ and constant nozzle-tank combination; uncertainties same as in Fig. 4.

and therefore $P_B^+ = P_B/P_i$, are held approximately constant and several vessel/nozzle combinations are examined. Although the characteristic times for the extreme cases differ by nearly two orders of magnitude (Table 1), when plotted in this dimensionless format, the data for all cases collapse to a fairly narrow band about the adiabatic and isothermal theoretical predictions. This result is pedagogically useful in reinforcing dimensional analysis concepts. However, the trends described above, that the faster discharges agree more closely with

the adiabatic theory while the slower ones agree better with the isothermal theory, are also discernible in Fig. 5(a). Figure 5(b) shows the results of a series of experiments in which the initial pressure, and therefore P_B^+, are varied for the same vessel/ nozzle combination. These experiments demonstrate that a single curve describes the dimensionless pressure/time history for choked flow, but that the unchoking point and the asymptotic value of P^+ at long times depend on P_B^+. Since the discharges plotted in Fig. 5(b) are all relatively

fast ones, taking on the order of 10 s or less, only the adiabatic theory has been plotted to avoid clutter. The agreement between the data and the theoretical predictions is excellent.

Results from typical vessel filling experiments are shown in Fig. 6. As was done for the discharge results, Fig. 6(a) presents data and predictions for the fastest charging experiment (approximately one second), while Fig. 6(b) does so for the slowest one (about 100 s). Clearly, the agreement between the data in Fig. 6(b) for the slow charging process agree very closely with the isothermal theory. While the data in Fig. 6(a) for the fast filling process are shifted somewhat toward the prediction of the adiabatic model, they still lie closer to the isothermal prediction. This result can be explained by the observation that for vessel filling enhanced forced convective heat transfer occurs, compared to vessel discharge, due to jet impingement phenomena on the walls
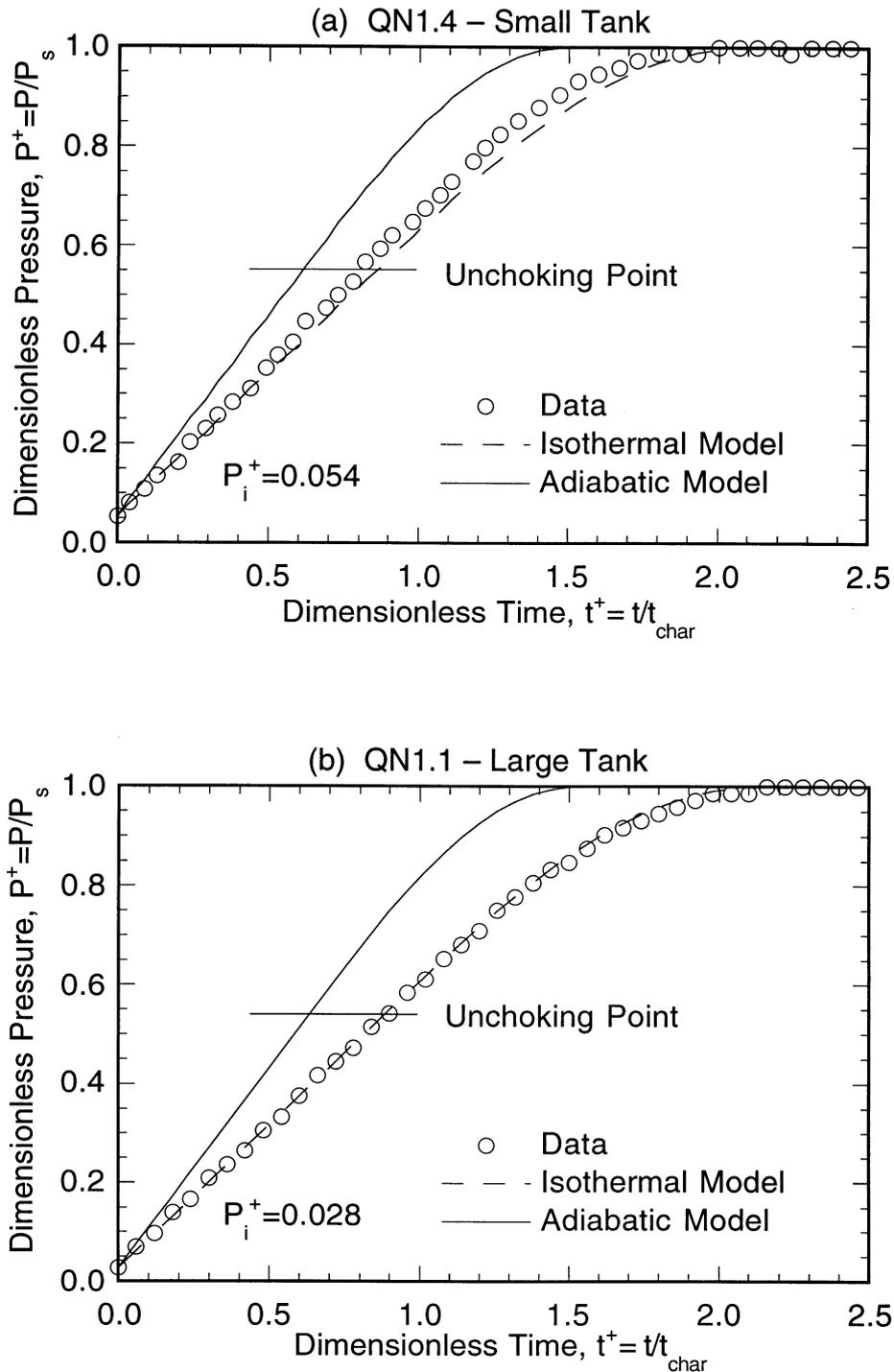

Fig. 6. Example single experiment data for the filling experiment: (a) nozzle QN1.4—small tank, (b) nozzle QN1.1—large tank; uncertainty in $P^+ = \pm 0.015$ and in $t^+ = \pm 0.08$ to 95% confidence.

J. C. Dutton and R. E. Coverdill

of the tank. In addition, the heat capacity of the tank walls is estimated to be more than an order of magnitude greater than that of the gas. Thus, even for rapid filling, substantial heat transfer between the gas and the vessel walls occurs and the gas temperature remains approximately constant. This hypothesis is again qualitatively confirmed by the thermocouple measurements.

Composite results for two series of experiments in which the vessel/nozzle geometry and initial pressure ratio $P_i^+ = P_i/P_s$ were varied are shown in Figs 7(a) and 7(b), respectively. In Fig. 7(a) the data for four vessel/nozzle combinations at an approximately constant value of P_i^+ are seen to collapse near the isothermal theory, although the expected trends with experiment characteristic time can be discerned. Figure 7(b) presents results in which P_i^+ was varied for a given vessel and nozzle, including the upper two curves for which the entire filling process was unchoked. For this
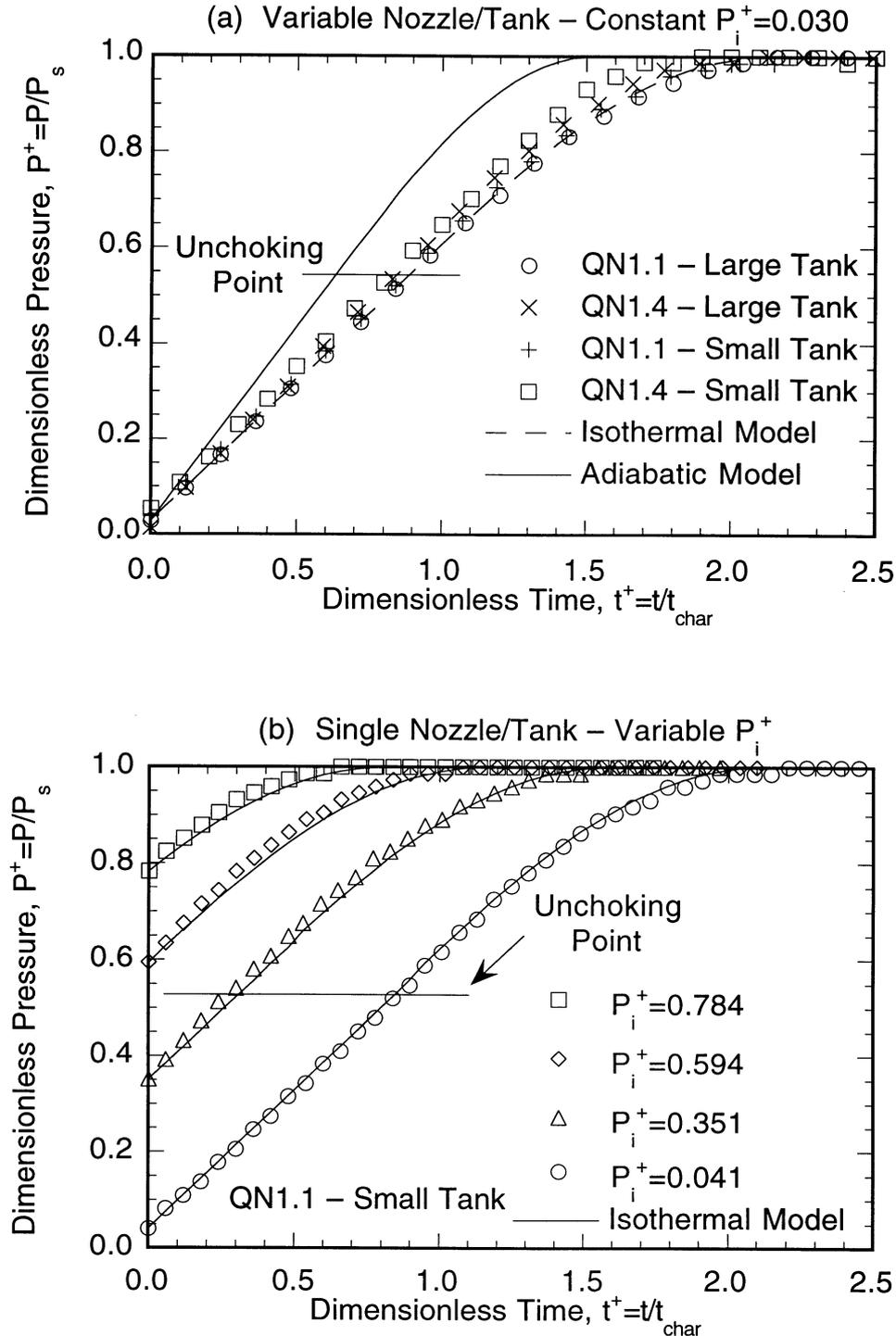

Fig. 7. Example composite data for the filling experiment: (a) variable nozzle/tank combinations and constant P_i^+, (b) variable P_i^+ and constant nozzle/tank combination; uncertainties same as in Fig. 6.

vessel and nozzle, the experiments require a filling time of about 15 s or less. In all cases the isothermal theory, which is clearly the superior one for the cases investigated here, is in close agreement with the data.

All of the experimental results presented here have been for cases in which converging nozzles were used. This is because these nozzles provide the extremes in the experimental characteristic times with the current equipment (Table 1). However, use of both the converging and converging-diverging nozzles illustrates the differences in choking characteristics of these two designs, in particular that the converging-diverging nozzles remain choked over a larger range of pressure ratios than do the converging nozzles.

SUMMARY AND CONCLUSIONS

Experiments to study the discharge of compressed gas from a pressure vessel and filling of an initially evacuated tank are described. Theoretical solutions for the two processes, incorporating both adiabatic and isothermal models, are also presented and compared to example measurements from the experiments. In each case, the agreement between the experimental data and theoretical predictions is found to be quite good.

In addition to demonstrating the accuracy of the one-dimensional theories developed here, these experiments can be used in open-ended experimental design situations. One possibility would be to introduce the students to the theoretical solutions and the available equipment and then ask them to design experiments that determine the range of parameters over which each model, adiabatic or isothermal, is the more accurate. Another possibility would be to pose an industrial application, such as a vessel discharge or filling accident scenario, for which the parameters (such as vessel size, opening area, initial pressure, or initial temperature) are far outside those that can be achieved in the laboratory. The students can then be asked to design experiments that answer questions concerning the time for vessel discharge or filling, the pressure, temperature, and mass flow time histories, etc. for the posed scenario. To answer these questions, the students obviously must identify the pertinent dimensionless variables, either by non-dimensionalizing the governing equations or by using the Buckingham Pi procedure, before proceeding with the experiments. Other open-ended experimental design experiences are also possible.

These experiments have been used in their current format for the last several years in a required senior-level thermal science laboratory course at the University of Illinois at Urbana-Champaign. In general, student feedback on the experiments is very positive. The experiments require substantial hands-on interaction, they make noise, and the students are particularly interested in the use of the digital data acquisition system and object-oriented LabVIEW programming language for acquiring the measurements. In addition, the data reduction is straightforward and is easily accomplished on a spreadsheet. Although safety is obviously a concern for the discharge experiment, because of the use of compressed gas, the filling experiment is extremely safe since only subatmospheric pressures occur. In summary, it is our experience that these experiments are excellent vehicles for demonstrating the fundamentals of unsteady, compressible flow. In addition, the analytical solutions that have been developed for the charging and discharging processes are useful in a number of practical applications.

REFERENCES

1. J. C. Dutton and R. E. Coverdill, Sudden discharge of a pressure vessel, *Laboratory Manual for ME 250: Thermal Science Laboratory*, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign (1994).
2. A. L. Addy and B. J. Walker, Rapid discharging of a vessel through a nozzle or an orifice, *ASME Paper 72-FE-40* (1972).
3. M. A. Saad, *Compressible Fluid Flow*, 2nd Ed., Prentice-Hall, Englewood Cliffs, New Jersey (1993) pp. 103–109.
4. J. A. Owczarek, *Fundamentals of Gas Dynamics*, International Textbook Co., Scranton, Pennsylvania (1964) pp. 254–256.
5. J. C. Dutton and R. E. Coverdill, Rapid filling of an evacuated vessel, *Laboratory Manual for ME 250: Thermal Science Laboratory*, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign (1993).
6. H. W. Coleman and W. G. Steele, Jr., *Experimentation and Uncertainty Analysis for Engineers*, Wiley, New York (1989).

J. Craig Dutton is the W. Grafton and Lillian B. Wilkins Professor of Mechanical Engineering at the University of Illinois at Urbana-Champaign. He received his B.S. from the University of Washington, his M.S. from Oregon State University, and his Ph.D. from the University of Illinois, all in Mechanical Engineering. His research activities consist of experimental studies of compressible fluid flows. He teaches undergraduate courses in

fluid mechanics and gas dynamics and graduate courses in gas dynamics. In addition, he has helped to develop the senior-level thermal science laboratory course. Two of the experiments from this course are the subject of the current paper.

Robert E. Coverdill is a Senior Research Engineer and Adjunct Lecturer in the Department of Mechanical and Industrial Engineering at the University of Illinois at Urbana-Champaign. He received a B.S. and M.S. in Mechanical Engineering from the University of Illinois. His research activity consists of engineering support for a wide range of projects in the department. He helped develop, and now teaches, the senior-level thermal science laboratory course. With several faculty members he has prepared many laboratory experiments and manuals in both thermal science and materials behavior for use with undergraduate courses.