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Using inverse models for determining orifices mass flow rate characteristics

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Abstract

Information concerning the flow rate of pneumatic components is essential for both selecting the right component at the design stage and validating different performances of a circuit. Recently, new procedures based on the measurement of the transient response for the charge or the discharge of a tank have been proposed. These procedures are corresponding to an inverse approach that enables the mass flow rate in a component to be identified. The presented work investigates these new approaches and discusses the problem related to the use of inverse models. The heat transfer problem, which appears to be the main difficulty, is illustrated in order to analyze the relevancy of the thermal hypothesis.

Keywords

Pneumatic, Inverse model, Heat exchange, Mass flow characteristic

Nomenclature

Physical parameters

b	: critical pressure ratio	
C	: sonic conductance	[m^3/s/Pa]
h	: specific enthalpy	[J/kg]
h_{conv}	: convection coefficient	[kg]
k	: polytropic index	
m	: mass	[kg]
P	: static pressure	[barA]
Q	: heat	[J]
$q_{h\,out}$	: outlet enthalpy flow rate	[W]
$q_{m\,out}$	: outlet mass flow rate	[kg/s]
S	: surface of thermal exchange	[m^2]
t	: time	[s]
T	: static temperature	[K]
U	: internal energy	[J/kg]
V	: volume of the tank	[m^3]
ρ	: density	[kg/m^3]

Physical constants

c_v	: specific heat at constant volume
r	: gas constant $= 287J/(kgK)$
γ	: ratio of specific heat $= 1.4$

Index and indices

0	: starting time of discharge
i	: generic time of discharge
r	: reference value
u	: upstream
d	: downstream
V	: tank
W	: wall of the tank
∞	: infinite time

1 Introduction

Although the mass flow rate characteristic of a pneumatic component has to be as accurate as possible for modeling purposes, only a reference associated to a specific procedure has to be defined in order to compare several components and to make a selection for design purposes. The difficulty in the case of the pneumatic technology relies on the lack of theoretical models allowing a simple and accurate characterization of the flow rate to be used both for modeling purposes and classification of components.
The ISO6358 standard [1] is based on a mathematical approximation of the mass flow rate characteristic and describes the experimental conditions and the bench assembly in the case of a constant section orifice. This mathematical approximation of the mass flow rate is a function of the pressure ratio and of the upstream pressure and temperature (1). Although the use of this standard is restricted to the characterization of single orifices, it proposes an approach that is usable both for modeling purposes and classification of components. However, the time and the need of an expensive equipment required to achieve the measurement using the 6358 standard are the main drawbacks for its extension in an industrial context.

$$\begin{cases} q_m = C\rho_0\sqrt{\dfrac{T_r}{T_u}}P_u\cdot\sqrt{1-\dfrac{\frac{P_d}{P_u}-b}{1-b}} \text{ if } \dfrac{P_d}{P_u}\geq b \\ q_m = C\rho_0\sqrt{\dfrac{T_r}{T_u}}P_u \text{ if } \dfrac{P_d}{P_u}<b \end{cases} \tag{1}$$

Recently, some other procedures based on the measurement of the transient response for the charge or the discharge of a tank have been proposed. Kagawa et al. [2, 3], Benchabane et al. [4] and Kuroshita et al. [5] have proposed such methods [6, 7] to identify the sonic conductance C and the critical pressure ratio b, the mass flow rate being obtained from the pressure response using an approximation of the solution of the tank state equation. These last procedures are corresponding to an inverse approach for identifying the mass flow rate in a component. Although it allows the experimental procedure to be shortened, the accuracy of the results are strongly related to the parameters of the experimental rig.
The presented work investigates one type of these new approaches, the discharge of a tank, and discusses the problem related to the use of inverse models in the case of identification problems.
The heat transfer problem, which appears to be the main difficulty when an inverse approach is used, is here illustrated in order to analyze the relevance of the thermal hypothesis (heat exchange, polytropic model). Although the isothermal chamber technique introduced by Kagawa [2] is an interesting but costly solution for solving the heat transfer problem, it is shown in this paper that any type of tank may be used if the heat transfer phenomena has correctly been identified. The results show the requirement of a precise model in order to reach the adequate accuracy needed for the extension of this approach to an usable orifice characterization procedure.

2 Thermodynamical model of a pneumatic chamber

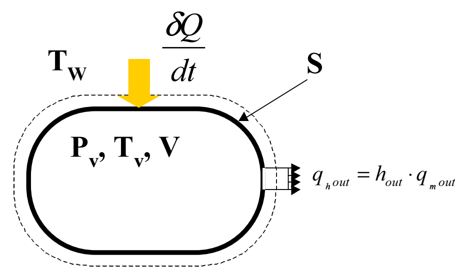

Figure 1: Pneumatic chamber

Considering the discharge of a tank (Figure 1), if the chamber volume is large enough, the kinetic energy of the fluid in the chamber can be neglected. The mass conservation law and the internal energy conservation law (2) enable the complete description of the dynamic behavior of the gas in the chamber. Considering the heat exchanged with the environment, without any mechanical work, the first law of the thermodynamics can be applied to this opened system.

$$\begin{cases} \dfrac{dm}{dt} = -q_{m\,out} \\ \dfrac{dU}{dt} = -q_{h\,out} + \dfrac{\delta Q}{dt} \end{cases} \tag{2}$$

With the hypothesis of a perfect gas, and assuming that, at any time, the pressure P_V, the temperature T_V and the density ρ_V of the gas are uniform in the chamber and equal to their mean value according to space, the state model of the system can be described by the following system of differential equations (4) using pressure and temperature in the volume as new state variables (3).

$$\begin{cases} P = \dfrac{r}{c_v V}\cdot U \\ T = \dfrac{1}{mc_v}\cdot U \end{cases} \tag{3}$$

$$\begin{cases} \dfrac{dP_V}{dt} = -\dfrac{r\gamma T_V}{V}\cdot q_{m\,out} + \dfrac{\gamma-1}{V}\cdot\dfrac{\delta Q}{dt} \\ \dfrac{dT_V}{dt} = \dfrac{(\gamma-1)T_V}{P_V V}\left(-rT_V q_{m\,out} + \dfrac{\delta Q}{dt}\right) \end{cases} \tag{4}$$

3 Inverse model

If we consider the complete discharge of a tank through an orifice (Figure 2), according to the ISO6358 standard [1], the determination of the mass flow rate characteristics of the orifice (critical pressure ratio b and sonic conductance C) requires the measurement of the mass flow rate through the orifice, the upstream and downstream pressures, and the upstream temperature. Assuming that the transient flow is negligible compared to the main flow, the mass flow rate passing through the orifice is equal, at any time, to the mass flow out from the tank.

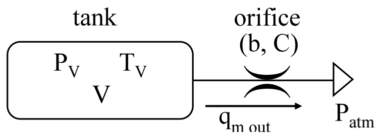

Figure 2: Scheme of a tank discharge through an orifice

Considering the previous system equation (4), and assuming that the pressure and temperature are known at any time, the determination of the output mass flow rate corresponds to an inverse problem. There are 2 equations and 2 unknown variables : the mass flow rate and the heat exchanged. The inverse model (5) shows that the pressure P_V and the temperature T_V have to be once differentiated. As P_V and T_V are obtained from measurements, a noise reduction procedure can be required.

$$\begin{cases} \dfrac{\delta Q}{dt} = \dfrac{\gamma V P_V}{(\gamma-1)T_V} \cdot \dfrac{dT_V}{dt} - V \cdot \dfrac{dP_V}{dt} \\[2ex] q_{m\,out} = -\dfrac{V}{rT_V} \cdot \dfrac{dP_V}{dt} + \dfrac{V P_V}{rT_V^2} \cdot \dfrac{dT_V}{dt} \end{cases} \tag{5}$$

4 Experimental results

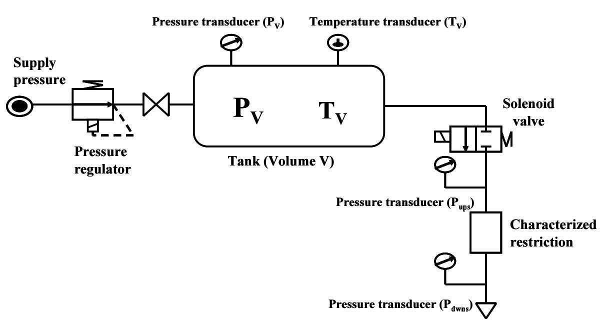

Figure 3: Experimental rig for the discharge method

In order to show a validation of this inverse methodology, the discharge of a standard steel tank (45 liters) through a 135° bend fitting (5 *mm* internal diameter) was realized (Figure 3). The initial pressure in the tank is imposed by the pressure regulator. When the initial pressure and temperature are stabilized in the tank, the solenoid valve is opened to start the complete discharge. Both pressure and temperature are measured in the tank, and additional pressure transducers enable the fitting upstream and downstream pressures to be recorded.

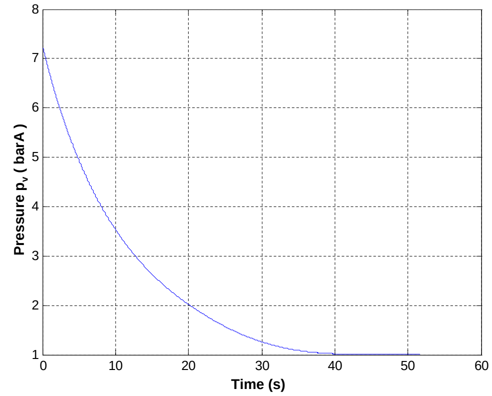

Figure 4: Measured pressure during the discharging process

The temperature was also indirectly measured using the '*stop method*' described by Kawashima [3]. The procedure consists in several partial discharges always starting from the same initial conditions (P_V^0 and T_V^0), which have to be the initial conditions of the complete discharge test. When the pressure in the tank reaches the value P_V^i, the discharge is interrupted by closing the solenoid valve, and the pressure P_V^∞ and the temperature T_V^∞ are measured. The mass of the gas in the tank being constant, it is possible to accurately calculate the temperature at which the discharge is stopped using the Charles law (6). Kawashima [3] has estimated that the error of this method is less than $0,3K$.

$$T_V^i = T_V^\infty \cdot P_V^i / P_V^\infty \tag{6}$$

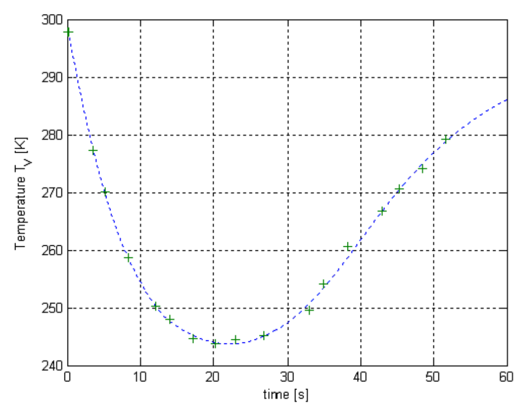

Figure 5: Measured temperature of the tank using the '*stop method*' and its approximation

Figure 4 shows the measured pressure during the discharge test from 7 bars to the atmospheric pressure. Figure 5 gives the measured temperature using the stop method and the polynomial approximation, which has been introduced to solve the inverse problem. Using the inverse model (5), the instantaneous mass flow rate and heat exchanged (Figure 7) can be computed from these data and their derivative. In this ideal case (Figure 2), computing the output mass flow rate and measuring the instantaneous pressure and temperature in the tank, enable the mass flow rate characteristic of the orifice through which the tank discharges to be determined (Figure 6), and the sonic conductance and the critical pressure ratio to be identified [1].

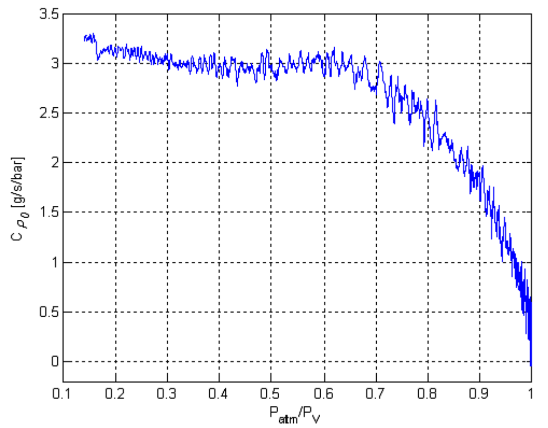

Figure 6: Mass flow rate characteristic $\frac{q_{m\,out}}{P_V} \cdot \sqrt{\frac{T_V}{T_0}}$ as a function of the pressure ratio $\frac{P_{atm}}{P_V}$

5 Heat exchange analysis

The thermal power exchanged during the discharge is now studied in order to verify if a polytropic law could describe pressure and temperature in the tank during this process, before developing a discussion on the use of a convection law.

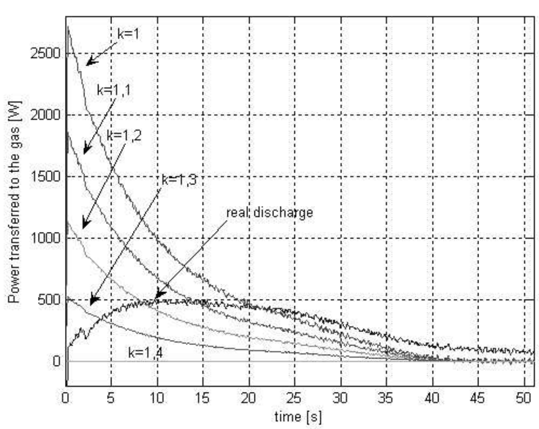

Figure 7: Evolution of thermal exchanged power

The heat exchanged computed from the inverse model (5) can be compared to the heat exchanged in the case of a polytropic evolution of the gas (7) considering different polytropic coefficient k but the same evolution of pressure in the tank. Using (4) in (7), the thermal power exchanged, considering a polytropic model to describe the discharge, is given by (8).

$$(1-k)\cdot\frac{dp}{P} + k\cdot\frac{dT}{T} = 0 \tag{7}$$

$$\frac{\delta Q}{dt} = -\frac{(\gamma-k)}{k(\gamma-1)}\cdot V\frac{dP_V}{dt} \tag{8}$$

According to equation (2) the exchanged power is considered positive when it is transferred from the environment to the gas. Figure 7 shows that the heat transfer reaches a maximum at the discharge half time, and though, that a polytropic law can not properly describe the heat transfer during the discharging process of the tank. However, figure 7 shows clearly the importance of the heat transfer during the discharge, and the need of a proper thermal exchange model in order to implement the discharge method using a standard tank.
Yingzi [8] and Benchabane [4] have also determined the polytropic index according to time in the case of a tank discharge. Considering a global polytropic transformation between the initial time t_0 and the time t and using equation (9), figure 8 confirms obviously the results of the previous works showing a large variation of the polytropic index during the discharge going from nearly an adiabatic process to an isothermal one.

$$k_{t_0}(t) = \frac{1}{1-\frac{ln(\frac{T_V}{T_V^0})}{ln(\frac{P_V}{P_V^0})}} \tag{9}$$

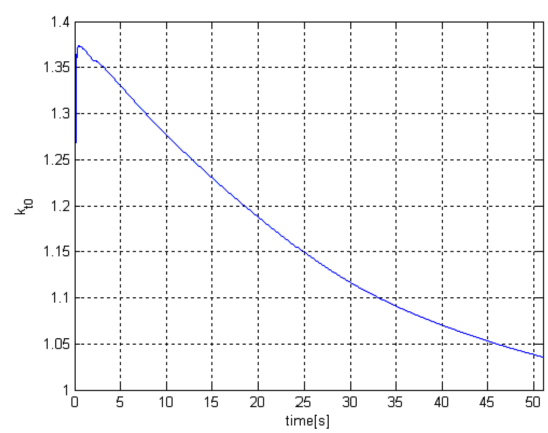

Figure 8: Polytropic index according to time calculated from initial conditions P_V^0, T_V^0

It is thus necessary to study more precisely the heat exchanges taking place between the gas in the tank and the environment. Classical hypotheses used in pneumatic chambers rely on the assumption that the thermal conductivity and the heat capacity of the wall material are sufficiently large compared to those of air, the wall temperature is therefore considered as a constant and the heat exchanged can be described by a convection heat transfer model expressed by the Newton's Law using a convection coefficient h_{conv}.

$$\frac{\delta Q}{dt} = h_{conv} \cdot S \cdot (T_W - T_V) \tag{10}$$

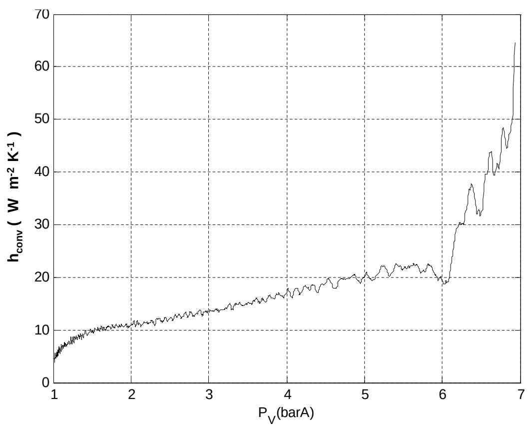

Figure 9: Convection coefficient vs tank pressure during the discharge process

Figure 9 confirms that the convection coefficient h$_{conv}$ is not a constant, but is a function depending on the flow characteristics. Several models are used in the litterature. For example, Yingzi [8] has proposed a convection coefficient that varies from a reference value as a function of both relative pressure and mass flow rate. Det [9] has used a simplified Eichelberg's model [10] to calculate h_{conv} (11), where h^r_{conv} is the convection coefficient corresponding to the reference pressure P^r_V and temperature T^r_V. Considering P^0_V and T^0_V as the reference pressure P^r_V and temperature T^r_V, Figure 10 shows that this model is still unable to give a correct evaluation of h_{conv} for the whole time range.

$$h_{conv} = h^r_{conv}\sqrt{\frac{P_V \cdot T_V}{P^r_V \cdot T^r_V}} \tag{11}$$

The previous results show clearly that the heat exchange phenomena is complex. Further works have to be carried on to overcome this problem both for simulation accuracy and proper orifice characterization; the isothermal discharge seems nowadays the best way to avoid this problem.

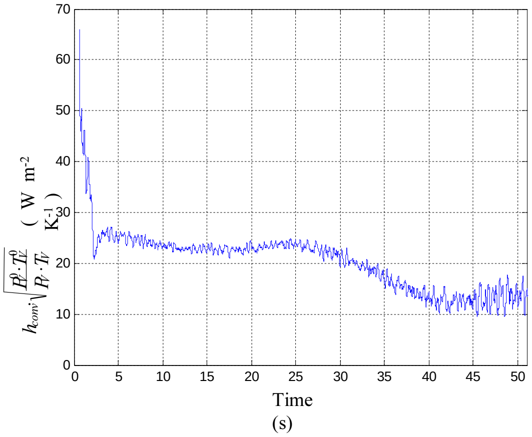

Figure 10: Variation of h from Eichelberg's simplified model

6 Limitation of the inverse approach

The main limitation of the inverse methodology is the difficulty of the measure of the instantaneous temperature due to thermocouples time response. Different solutions have been proposed such as the indirect measure of the temperature by the '*stop method*', but this method is time costly since each measured point of temperature requires the stabilisation of the pressure and of the temperature in the tank. This method is nevertheless interesting for the identification of the thermal hypothesis for a type of tank [2].
The NF E49-300 standard [7] is based on slow discharges (2 to 5 minutes) for which the time response of the thermocouple can be neglected. But it requires very large tanks. Moreover the thermocouple location in the tank [5] can be critical on which temperature is really measured.
Kagawa [2], and subsequently the japaneese standard [6] avoid this problem by using an isothermal tank. But the difficulty is the implementation of this isothermal tank, its costs and its lifetime (conservation of its isothermal property in the time with the materials pollution).
A last solution that avoids the measure of the temperature, relies on either the knowledge of the heat exchanged for a given tank or the use of an accurate thermal exchange model. Then, according to our hypotheses, the inversion problem consists to solve a single non linear differential equation (12) that gives T_V and to use the output equation (13) for determining the mass flow rate $q_{m\,out}$:

$$\frac{dT_V}{dt} = \frac{(\gamma-1)T_V}{\gamma P_V V}\left[V \cdot \frac{dP_V}{dt} + h_{conv} S(T_W - T_V)\right] \tag{12}$$

$$q_{m\,out} = -\frac{V}{\gamma r T_V} \cdot \frac{dP_V}{dt} + \frac{(\gamma-1)}{\gamma r T_V} \cdot h_{conv} S(T_W - T_V) \tag{13}$$

Then it is possible to obtain the temperature and the output mass flow rate only from the tank pressure measurement. At this state of our research, this methodology has to be validated in regard with:

- the existence or the identification of a correct model of the heat exchange term associated to a given tank, which has necessarly to take into account the variation of the convection coefficient,
- the repeatability and the precision of the procedure, firstly using the same experimental rig but realizing discharges from different initial pressures, and secondly testing with different types of orifices.

7 Conclusion

The proposed approach shows that it is possible to compare different components to each other using the discharge procedure with a normal tank. The only condition is that the heat exchanged model must be well-known. This requires a first precise study of the tank to be used. It has been done in our case by an indirect measure of the temperature using the stop method enabling the heat exchanges to be known by the resolution of the inverse model.
This study of the heat exchanges in the tank has shown the necessity of a better knowledge of them and thus the elaboration of other macroscopic models than the classically used polytropic ones.
The inverse methodology has to be extended to cases where it is not possible to make all the restrictions negligible compared to the orifice to be characterised. This could also avoid on one hand the oversizing of the experimental rig used for the discharge method, and on the other hand the design of specific equipments (fittings, pressure tubes,. . .).

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