DYNAMICS OF KNOCK-OPEN VALVE FOR GAS GUNS POWERED BY CARBON DIOXIDE

Linh DO DUC*, Vladimír HORÁK*, Tomáš LUKÁČ*, Roman VÍTEK*
Quang Huy MAI,**

*University of Defence, Brno, Czech Republic
**Le Quy Don Technical University, Hanoi, Vietnam
(duclinh.do@gmail.com, vladimir.horak@unob.cz, tomas.lukac@unob.cz,
roman.vitek@unob.cz, maiquanghuykvk@yahoo.com.vn)

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Abstract: *The paper is focused on the dynamics of knock-open valve used to control the mass flow from a carbon dioxide (CO_2) reservoir. The objective is to formulate the mathematical model simulating dynamics of the knock-open valve system for the gas guns powered by carbon dioxide. The equilibrium discharge mathematical model is overviewed, modified and evaluated to obtain the thermodynamic equilibrium states taking place within the reservoir. The problem is solved using MATLAB environment and results of theoretical solution are verified experimentally. Influence of changes in some design parameters of the knock-open valve system to the mass discharge of CO_2 within the reservoir is comprehensively examined.*

Keywords: *knock-open valve, gas gun, carbon dioxide, airsoft, paintball, pressure reservoir.*

1. INTRODUCTION

In recent years, the knock-open valve is one of the most commonly used gas valves in gas guns technology due to its outstanding reliability, ease of maintenance and long service life. Besides, the only drawback of knock-open valve is extreme sensitivity to working gas pressure. If the reservoir is over-pressurized that means the pressure within the reservoir is higher than the design of the action can accommodate, the valve cannot be opened as far as it should by the hammer, therefore less gas discharges and consequently lower performance. The over-pressurization commonly appears in the case of carbon dioxide reservoir, when the surrounding temperature gets higher than the critical value.

The knock-open valve system plays a critical role in controlling the gun's performance, because its design parameters and set up determine the mass flow from the pressure reservoir into the barrel. In other words, the guns performance controlling problem can be solved, if we are able to discharge the gas out of the reservoir on command.

Hence, it is crucial to obtain a scientific understanding of knock-open valve dynamics and further the dependence of thermodynamic properties within the reservoir on the valve design parameters. In order to satisfy this goal, a comprehensive discharge mathematical model including the knock-open valve dynamics is required.

There is almost no published literature on the topic mentioned above. Several related publications have appeared in the last few years documenting the study of phase behavior of carbon dioxide as the power gas for gas guns [1], in which a comprehensive equilibrium discharge mathematical model for CO_2 has been developed, the complex internal ballistics models of gas guns were presented in [3,4] and the simulation of the sound effect of RPG-7 anti-tank grenade launcher for shooting training is given in [2]. All these above mentioned works deal with the gas discharge from a pressure reservoir through a control valve system that was treated only as an orifice of a constant cross-sectional area meaning that the dynamics of the valve was neglected.

In this paper, a comprehensive mathematical model simulating the knock-open valve dynamics is formulated. The equilibrium discharge mathematical model for carbon dioxide tanks presented [1] in order to simulate the thermodynamic states taking place inside the reservoir is overviewed and evaluated. For the purpose of verifying the model an experimental setup has been established.

2. PRINCIPLE OF KNOCK-OPEN VALVE OPERATION

Figure 1 shows the basic concept of a knock-open valve consisting of a valve body, a valve stem and a return spring. The valve body is connected with a gas reservoir that in this study is filled with liquefied carbon dioxide. In the case of closed valve, the hammer is held in the back position while the valve is blocking its way by the return spring force and the pressure force generated by the high-pressure CO_2 vapor. In order to prevent gas escaping from the valve through the valve face, a sealing O-ring is used.

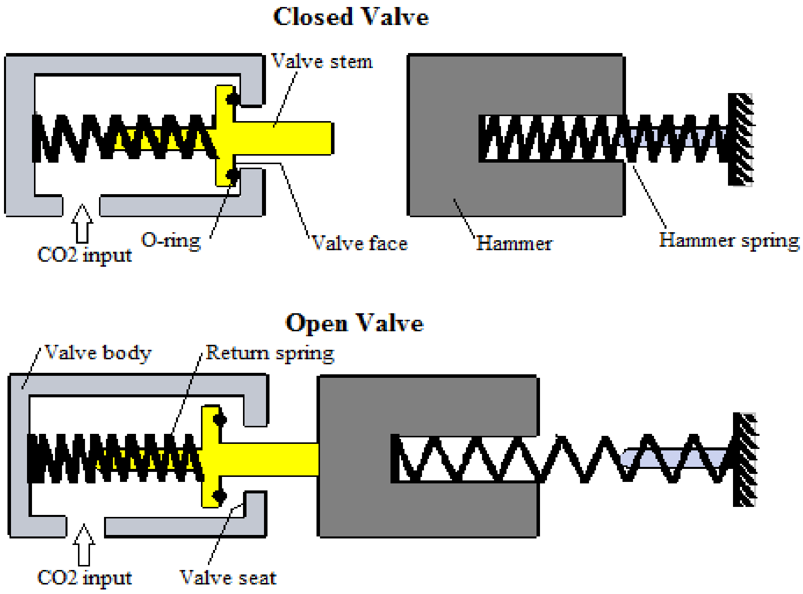

FIG. 1. Schematic of the knock-open valve

Once the hammer is released, it is driven forward by the hammer spring force, then it strikes the end of the valve stem. After that, the valve stem and the hammer move together forward, therefore the contact between the sealing O-ring with the valve face is broken, forcing the valve to open and release the pressurized CO_2 vapor. The valve return spring has been overcome by the power of the hammer, but after a short time, with help of the pressure force of CO_2 vapor in the reservoir, it will reverse the direction of the valve stem and close the valve again to further gas flow.

3. MATHEMATICAL MODEL

As it is seen in Fig. 2a, the reservoir is considered as an open thermodynamic system, in which we assume that CO_2 exists in liquid-vapor equilibrium. The vapor phase occupies the upper part of the reservoir and the bottom reservoir portion is filled by the liquid phase. There exists an interface between the two phases. If all the assumptions provided [1] for the vapor discharge of carbon dioxide tanks are accepted, we are able to apply the equilibrium discharge mathematical model presented in [1] in order to assume the thermodynamic equilibrium states inside the reservoir at every point in time throughout discharging under ambient temperature conditions. This model enables us to determine the time change in pressure and mass.

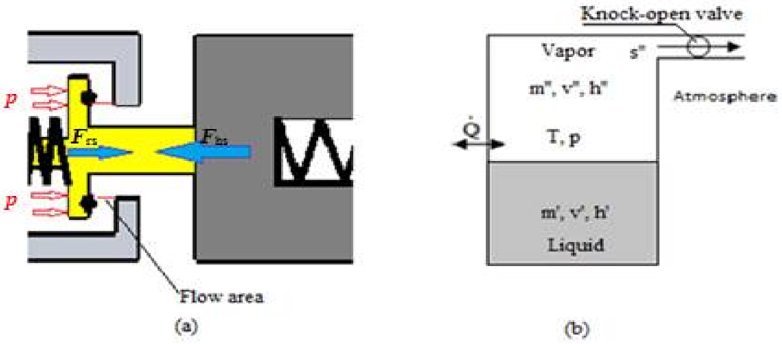

FIG. 2. (a) Schematic of forces acting on the hammer-valve stem system, (b) Reservoir as an open thermodynamic system

The equilibrium discharge mathematical model for the CO_2 reservoir consists of following equations [1]:

$$\frac{dT}{d\tau}=\frac{\frac{dQ}{d\tau}-\dot{m}v''\frac{L(T)}{\Delta v}}{m\tilde{c}_P(T)-\frac{V_R}{T}\frac{L(T)}{\Delta v}-L(T)\phi(T)} \tag{1}$$

$$\frac{dx}{d\tau}=-\frac{1}{m}\left(\frac{v}{\Delta v}\frac{dm}{d\tau}-\phi(T)\frac{dT}{d\tau}\right) \tag{2}$$

$$\frac{dm''}{d\tau}=-\frac{v'}{\Delta v}\frac{dm}{d\tau}-\phi(T)\frac{dT}{d\tau} \tag{3}$$

$$\frac{dQ}{d\tau}=\alpha A\left(T-T_w\right) \tag{4}$$

$$\frac{dm}{d\tau}=-\dot{m}=-C\frac{\upsilon A}{v} \tag{5}$$

where:

T	Temperature of CO_2 within reservoir	V_R	Total volume of reservoir
T_w	Temperature of reservoir wall	α	Heat transfer coefficient

m''	Mass of vapor phase	A	Flow area
m	Total mass of CO_2	C	Discharge coefficient
$\dot{m}$	Mass flow rate through valve system	υ	Discharge flow velocity
Q	Heat	Δv	Difference of specific volumes ($v''-v'$)
v	Specific volume of CO_2	L	Latent heat
v''	Specific volume of vapor phase	$\tilde{c}_P$	Mixture heat specific capacity
v'	Specific volume of liquid phase	x	Quality of two-phase mixture
υ	Discharge flow velocity	ϕ	Substitution function of temperature

In contrast to the equilibrium discharge model provided by the author in [1] flow area A indicated by the read lines in Fig. 2a is not a constant and its size depends on the displacement of the valve stem l_{st}. The value of A can be expressed as follows

$$A = \pi D_{Or} l_{st} \tag{6}$$

where D_{Or} is the sealing O-ring diameter. As it is seen in Eq. (6), to close the mathematical model it is necessary to solve the dynamics of the hammer-valve stem system to obtain the value of the valve stem displacement l_{st}. In order to satisfy this goal, first of all we assume that the collision between the hammer and the valve stem is perfectly elastic collision. It means that the hammer and the valve stem are stick together after the collision and there is no kinetic energy loss. Thus, we can write Newton's Second Law for motion of the hammer-valve stem system in following form

$$\frac{dV_{st}}{d\tau} = \frac{F_{hs} - F_{rs} - F_P}{m_h + \dfrac{m_{hs}}{3} + m_{st} + \dfrac{m_{rs}}{3}}, \qquad \frac{dl_{st}}{d\tau} = V_{st} \tag{7}$$

where m_h, m_{hs}, m_{st} and m_{rs} account for the mass of hammer, hammer spring, valve stem and return spring, respectively. The V_{st} denotes for the hammer-valve stem velocity. Here, there are three forces acting on the hammer-valve stem system (see Fig. 2a):

- The return spring force F_{rs} acting on the stem against the hammer spring force F_{hs}. Their value depend on the spring constants, the spring preload and displacement l_{st}.
- The pressure force $F_P = (p - p_a) A_{crs}$, where p is the reservoir pressure, p_a is the surrounding pressure at the knock-open valve output and A_{crs} represents for the cross-sectional area of the valve stem.

In this study, the friction force between the valve moving parts and surfaces is neglected.

Besides, it is needed to take the motion of the hammer before the collision with the valve stem in consideration in order to determine the hammer's impact velocity and further its impact kinetic energy. Before the collision, there is only the spring force acting on the hammer, therefore we apply Newton's Second Law again for hammer motion, we obtain the similar form of the equations of hammer motion as in Eq. (7), in which F_{rs}, F_P, m_{st} and m_{rs} are eliminated.

4. RESULTS OF SOLUTION

The above described problem was solved by numerical integration with MATLAB using the explicit fourth-order Runge-Kutta method. Mathematical model considers a range of input data parameters and boundary conditions (i.e. reservoir volume, initial temperature, the total mass of CO_2 and the percentage of liquid fill within the reservoir, the discharge coefficient, the heat transfer coefficient, etc.). In order to present results of solution, we chose the input data parameters and boundary conditions shown in Tab. 1 that correspond to the design parameters of the knock-valve-hammer system used in Tippmann A5 paintball gun. Results of the solution of the developed mathematical model for this given example are presented from Fig. 3 to Fig. 5.

Table 1. Initial data parameters and boundary conditions

Quantity	Value	Quantity	Value
Initial reservoir temperature (K)	22	Hammer spring constant (N/m)	807
Temperature of reservoir wall (K)	22	Hammer spring mass (g)	2.7
Total reservoir volume ($.10^{-3}m^3$)	0.8	Hammer mass (g)	140
Initial total mass of CO_2 (g)	360	Hammer stroke before collision (mm)	29.5
Initial mass of vapor phase (g)	89	Return spring constant (N/m)	10302
Discharge coefficient	0.7	Return spring mass (g)	1.6
Sealing O-ring diameter (mm)	10	Valve stem mass (g)	4.7

The change in mass of CO_2 within the reservoir is shown in Fig. 3a. Figure 3b indicates the percentage of the vapor phase mass within the reservoir is slightly increasing about 0.02%. It can be explained that, the amount of vapor discharged out of the reservoir is smaller than the amount of vapor generated by the vaporization of the liquid phase for the purpose of maintaining the thermal phase equilibrium inside the reservoir. This phenomena explains the wide range of use of CO_2 in the gas guns community from the point of view of the guns power and the reservoir capacity, i.e. number of shots per fill.

The dynamics of the knock-open valve system is clearly shown in Fig. 4. In the first phase of operation, the hammer is accelerating the beginning until the moment, when it starts colliding with the valve stem. At the end of this phase the hammer reaches the impact velocity v_{ip}. After that, the valve stem and the hammer move together, opening the valve gradually until the hammer is stopped. Then, the hammer changes its direction and moves to the back position that causes the valve to be closed successively. Simulation of the hammer motion after closing the valve is not the aim of this study due to its insignificant influence to dynamics of the knock-open valve.

Results obtained using the described mathematical model enable us to observe influence of changes in various design parameters. The gun’s performance is proportional to the amount of CO_2 discharged from the reservoir into the barrel through the knock-open valve during each shots. Figure 5a shows the influence of the hammer impact velocity v_{ip} to the mass discharge of CO_2 (i.e. amount of discharged CO_2). It is seen that the mass discharge reaches its maximum value at the so called critical hammer impact velocity v_{cr}. If the impact velocity oversteps the critical value, it causes the mass discharge to decrease due to decreasing in opening time of the valve (red curve). Figure 6 illustrates the way to choose the correct design value of hammer mass and hammer spring constant to obtain the required impact velocity. The mass discharge can be also controlled by changing the size of flow area that is function of the sealing O-ring diameter (Fig. 5b).

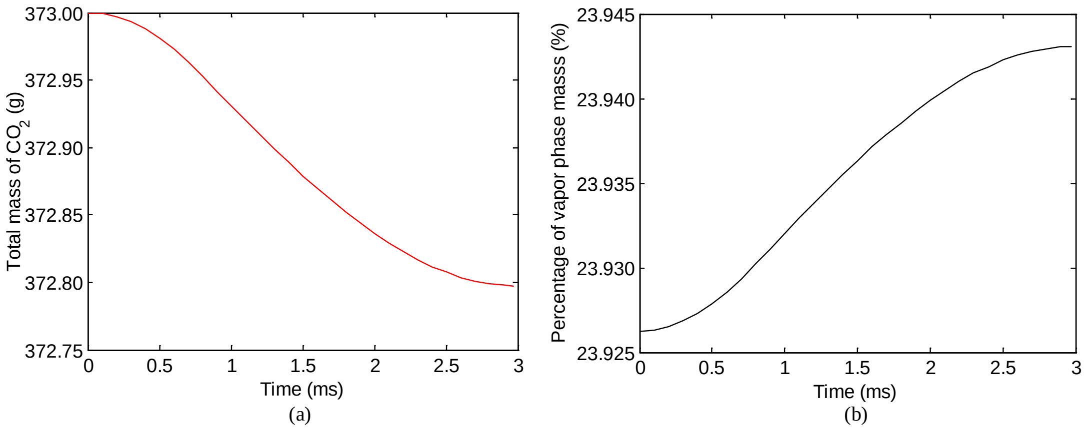

FIG. 3. Time courses of total mass (a) and percentage of vapor phase mass (b) within the reservoir

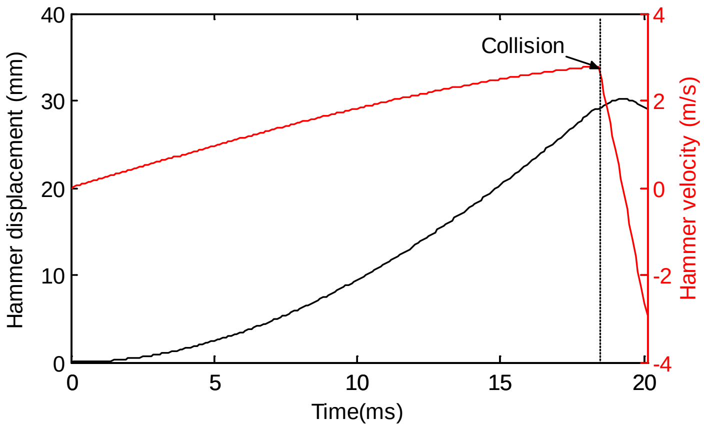

FIG. 4. Hammer displacement (black) and hammer velocity (red) versus time

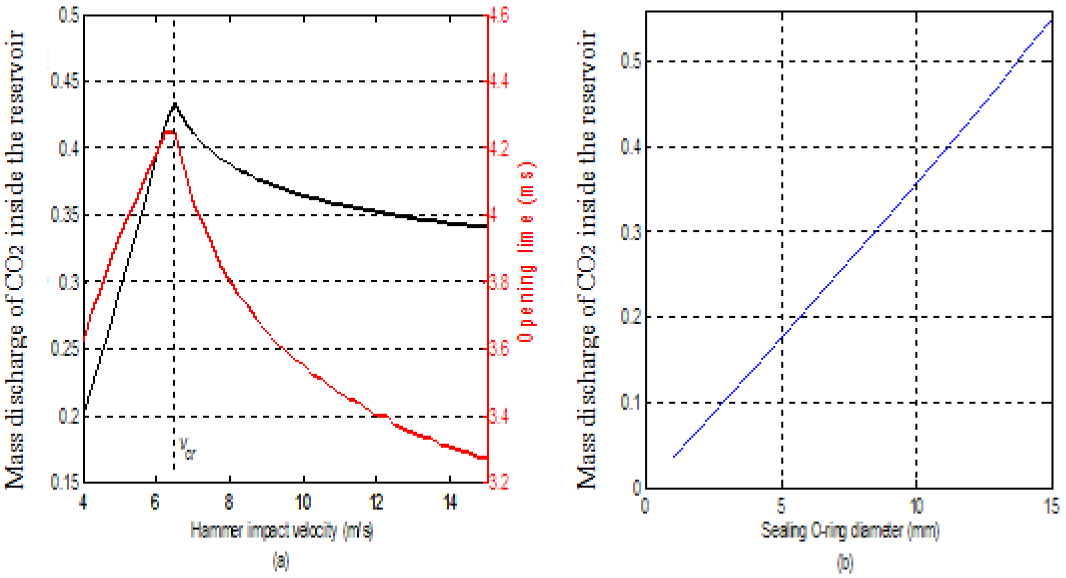

FIG. 5. (a) Influence of the hammer impact velocity and opening time (a) and size of flow area (b) to the mass discharge of CO_2 inside the reservoir

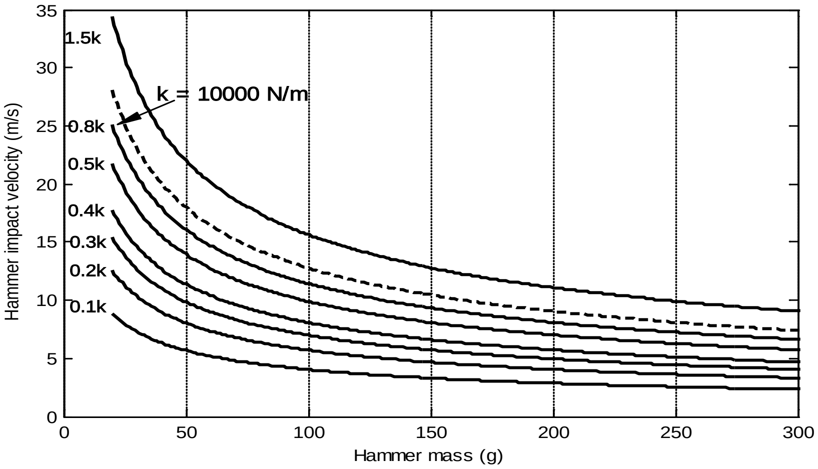

FIG. 6. Hammer impact velocity as a function of hammer spring constant and hammer mass

5. VERIFICATION OF THE MATHEMATICAL MODEL

Results of solution of the hammer and valve stem displacement and the CO_2 mass discharge are compared with the measured values. The displacement of the hammer was measured using high speed camera FASTCAM Mini UX100 type 800K-M-4G, the chosen record rate was 10000 frames per second, the shutter speed was 1/80000 (s). The compassion of calculated and measured time courses of the hammer displacement is shown in Fig. 7.

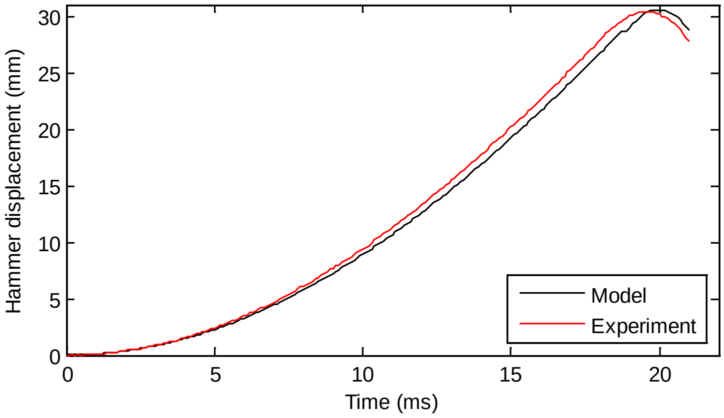

FIG. 7. Hammer displacement vs. time

Table 2. CO_2 mass discharge after opening the valve five times

Hammer mass (g)	CO_2 mass discharge (g)		Difference (%)
	Experiment	Model	
142.6	2.02	1.961	2.92
134.0	2.01	1.960	2.48

The valve is opened five times consecutively and then the CO_2 mass discharge was measured using a precision digital scale. Here two hammers of different masses were used. The calculated and measured mass discharge values are compared in Tab. 2, from that we can conclude quite good agreement between the results of the mathematical model and experimentally obtained values.

CONCLUSIONS

In this study, the mathematical model for analyzing the dynamics of the knock-open valve system for the knock-open valve has been formulated. The equilibrium discharge mathematical model has been overviewed, modified and evaluated. The problem has been solved in MATLAB environment. Obtained results enable us to analyze various influences of changes in several design parameters. This model can be used as the base for the design and optimization of the knock-open valve system.

The presented mathematical model was verified experimentally by measuring the hammer displacement and the mass discharge of CO_2 within the reservoir. It can be stated that the theoretical solution correspond quite well with experimental measurements. As the future improvement of experimental device, the range of hammer mass will be wider and the flow area size will be changed.

AKNOWLEDGMENT

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