A New Venting Valve for Anti-colic Nursing Bottles

Meitham Amereh[1], Sina Kheiri[2], Keekyoung Kim[2], Ri Li[2] and Mohsen Akbari[1]

[1]Laboratory for Innovations in Micro Engineering (LiME), Department of Mechanical Engineering, University of Victoria, Victoria, Canada
[2]School of Engineering, University of British Columbia, Kelowna, BC, V1V1V7, Canada

Abstract— **Conventional nursing bottles are completely sealed except for the small hole on the teat. Without appropriate venting, the interior partial vacuum can increase the incidence of otitis and gastrointestinal disorders in infants. This study presents the design, modeling and fabrication process of new venting system for the nursing bottle. Finite element (FE) and fluid-structural interaction (FSI) analyses were carried out to show the transient response of both fluid flow and flexible structure of the valve to the pressure difference. In addition, experimental system was established for testing and analyzing the performance of different valves.**

Keywords— **Nursing bottle, venting valve, finite element analysis, fluid-structural interaction**

I. INTRODUCTION

Bottle-feeding is extremely important for the healthy growth and development of infants. As common as breastfeeding, a large number of infants throughout the world rely solely on bottle-feeding [1-3]. Moreover, most breastfed infants also need to take bottle feeds and switch to bottle feeding as they grow [4-6]. Conventionally, nursing bottles are entirely sealed except for the small opening on the teat for delivering milk. [7]. During feeding, infants suck the teat to withdraw the milk out of the bottle and hence air enters the bottle through the teat to compensate the reduced volume of liquid. As a result, air bubbles are formed in the milk near the teat. When the infants keep sucking on the teat, these small air bubbles are often ingested by the infants. The ingestion of the air bubbles leads to colic and other gastrointestinal disorders. The unwanted ingestion of air is a long-recognized problem in the infant feeding [8–12]. Several designs have been proposed to reduce the air ingestion of infants [13–15], however, this design still generates a partial vacuum inside the bottle called under-vented condition.

This paper presents a new venting mechanism for a fully vented nursing bottle. The bottom cavity of the bottle was assembled with a flexible valve which was fabricated by an inexpensive and novel fabrication process. The air flows through self-adjustable valve during the sucking; however, it prevents leakage when the negative pressure caused by sucking is removed. This capability of the valve to let the air flow through the bottle helps infants normal feeding and prevents adverse effects of negative pressure inside the bottle. Air does not mix with the milk as well, which minimizes oxidation and keeps the essential nutrients.

II. METHODOLOGY

A. Concept and design

The proposed method utilizes a novel venting valve mechanism connected to the bottom of the bottle as shown in Figure 1 (A-B). The hemispherical part of the proposed design enables the valve to respond two opposite reactions under pressure difference. The hydrostatic positive pressure inside the bottle pushes the hemispherical surface to the center of the curve. Integration of this pressure over the valve surface has a component in the surface of the cuts, which compress leaflets together to close the valve. The more pressure is applied to the leaflets, the more force acts to close the valve. This condition occurs when the bottle stands up and the liquid inside the bottle exerts the positive hydrostatic pressure on top of the valve. On the other hand, when the amount of liquid inside the bottle decreases because the liquid flows out through the nipple as the infant sucks the milk, the decrement of the liquid generates the partial vacuum inside the bottle, as shown in Figure. 1 (C). This vacuum exerts a negative pressure on top of the hemispherical surface and pulls the leaflets inward to open the crosscut to compensate the inside negative pressure until the end of sucking cycle.

B. Synthesis and characterization of materials

Liquid silicone rubber (LSR, Shenzhen Lianuan silicone Rubber Co, China), which is a widely used material for nipples in nursing bottles fabrication, was used to fabricate the venting valve. The mechanical property of the cured LSR was measured by a mechanical testing machine (Mach-1, Biomomentum Inc., Laval, QC, Canada). Figure 1 (D) shows testing specimens with 2mm thick and 8mm in dimeter cut out from a cured sample to be tested under the compressive load. Young’s modulus was calculated as 3.7Mpa ± 0.23, as shown in Figure 1 (E).

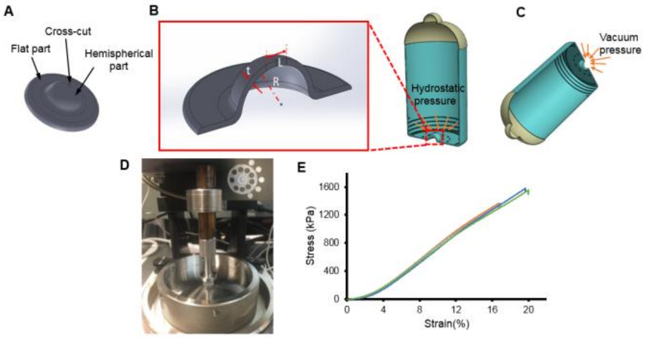

Fig. 1. Valve design and mechanical properties characterization. (A) Schematic illustration of the valve. (B) Schematic of bottle equipped with valve under hydrostatic pressure. (C) Schematic of bottle equipped with valve under inside vacuum pressure. (D) LSR samples under mechanical test machine. (E) Stress-Strain curves for cured LSR samples to calculate average Young's Modulus.

C. Fabrication and Assembly of Venting Valve

Due to the high curing temperature condition of the LSR, we fabricated two parts of aluminum molds, shown in Figure 2 (A). Two components were mixed and placed in a vacuum to degas the solution. The degassed compound was first poured into the negative mold, and positive mold was then placed to pair the mold. Figure 2 (B) shows a valve cured at 180°C for 10 minutes. The valve was flexible, smooth and transparent. After casting, a crosscut was made by surgical blade on the hemispherical part of the valve to form the leaflets, shown in Figure 2 (C). The valve was fixed with a clip and an adjustable size washer was used to restrict the cutting area for the blade. The flat part of the valve was bonded to the bottle bottom using epoxy and the valve assembly was screwed to the body of the bottle Figure 2 (D-F).

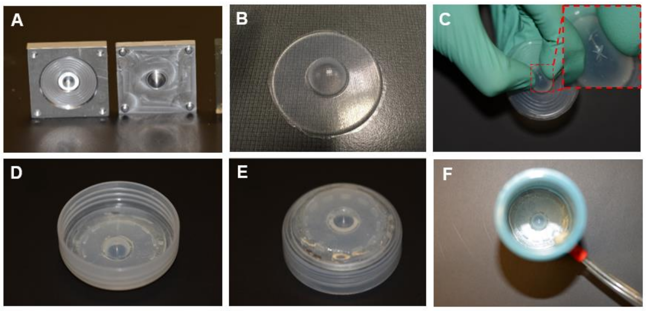

Fig. 2. Fabrication of the venting valve. (A) Aluminum molds. (B) Synthesized valve by curing LSR. (C) Making crosscut on helispherical part of the valve. (D) Top view of bonded valve to the bottom of the bottle. (E) Bottom view of bonded valve to the bottom of the bottle. (F) Bottle equipped with the valve and sensor tubing.

D. Computational simulation

FEM and FSI analyses were performed in ANSYS workbench to study both static and transient responses of the venting valve to the pressure change. The valve geometry was designed in SolidWorks imported to the static structural toolbox in ANSYS. The flat part of the valve is defined as a fixed support in all directions. The force is being applied at each point normal to the hemispherical part of the valve to simulate the effect of the pressure difference. Also, FSI analysis was performed due to the strong interdependence between solid structure of the valve and the fluid flow.

E. Experimental setup

A set-up comprises of two low pressure sensors (Pasco PS-3203), vacuum pump, container and interface system was prepared, as shown in Figure 3 (A-B). Sensors were connected to the nipple and inside the bottle as well with several tubing. A vacuum pump was employed to produce suction pressure with different frequencies and suction amplitudes. Figure 3 (C) shows the typical graph of pressure change inside the bottle equipped with venting valve. The frequency of the breast pump was set to 1 Hz. Two different thicknesses and curvatures were firstly simulated and then experimentally tested to find their effects on the performance criterions, as shown in Table (1).

Table 1 The geometry of fabricated valves

Valve/Geometry	Thickness (mm)	Curvature radius (mm)
Valve #1	1.5	7.5
Valve #2	2	7.5
Valve #3	2	8.5
Valve #4	1.5	8.5
Valve #5 (one opening)	1.5	8.5

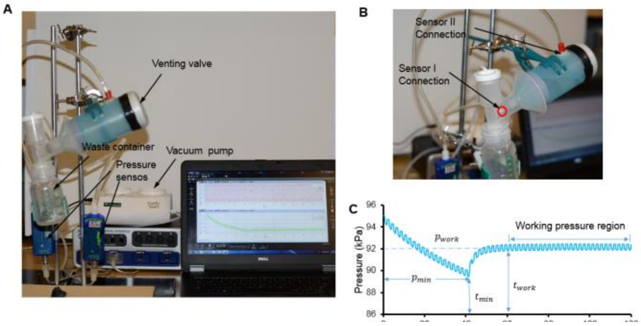

Fig. 3. Experimental tests. (A) Real set-up to simulate actual sucking condition. (B) Sensors connection to the nipple and inside of the bottle. (C) Typical graph of pressure changes inside the bottle with venting valve.

III. RESULTS AND DISCUSSION

Results of both static structural deformation and transient fluid-solid interaction in different valves were obtained to analyze the valve performance. For the FEA computational simulation, two cases were considered. In the first case, we studied the effect of the partial vacuum inside the bottle. A negative pressure, 4 MPa, was applied to the valve to intake the air into the bottle. Maximum deformations occurred at the edges around the center of cuts. Adjacent leaflets were touching each other and there was no structural connection between nearby elements. Therefore, as soon as the pressure overcame the friction between the walls, the free edges started moving outward to open the valve, letting the air flow through the opened valve. The distribution of equivalent (von-mises) strain and stress of the opened valve were obtained. In the second case, we assumed that the bottle was placed upward and hydrostatic pressure of a certain amount of milk was applied to the valve. By substituting the density of milk, $\rho_{milk} = 1.03g/mL$, gravitational acceleration, $g = 9.81m/s^2$, and the height of milk, $h = 15cm$, the hydrostatic pressure, $P = \rho gh$, was obtained as 1515 Pa. Figures 4 (A-F) summarize the results. The simulation result shows that the best venting could be achieved with valve #4.

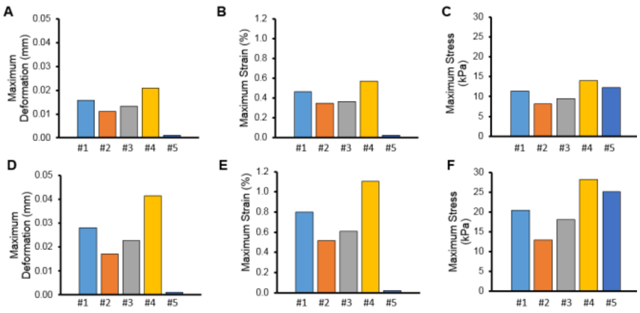

Fig. 4. FEA computational simulation of the five different for: Case I: hydrostatic pressure closes the crosscut, (A) deformation distribution, (B) equivalent (von-mises) strain distribution, (C) equivalent (von-mises) stress distribution. Case II: vacuum pressure opens the crosscut, (D) deformation distribution, (E) equivalent (von-mises) strain distribution, (F) equivalent (von-mises) stress distribution.

In FSI simulation, three geometries with different thickness and curvature were respectively analyzed; i) t=1mm and R=8.5mm, ii) t=2mm and R=8.5, iii) t=1mm and R=7.5mm. Figure 5 (A) shows the distribution of the mesh deformation in the valve #1 at the end of the one-second simulation. The leaflets were deformed more than other parts of the valve and the maximum deformation occurred at the center of the crosscut. Figures 5 (B-D) show the deformation of the leaflets at three different time steps, t=0, t=0.5 and t=1sec. As the pressure raises by the time, the force acting on the valve increases as well and deforms the leaflets further.

The pressure change inside the fluid region was analyzed in one second. Figure 6 (A) shows the pressure contour for the valve #1. The maximum pressure change occurs where the air passes through the gap between leaflets. Figure 6 (B) shows the pressure change along central axis of the fluid, connecting center points of the inlet and outlet of the valve #1, for t=0.45s and t=0.88s. This graph illustrates that the pressure in the center of the cavity near the inlet is close to 2kPa and drops while the flow reached the leaflets. Figure 6 (C) shows the pressure profile on the valve#1 at t=0.45s and t=0.88s.

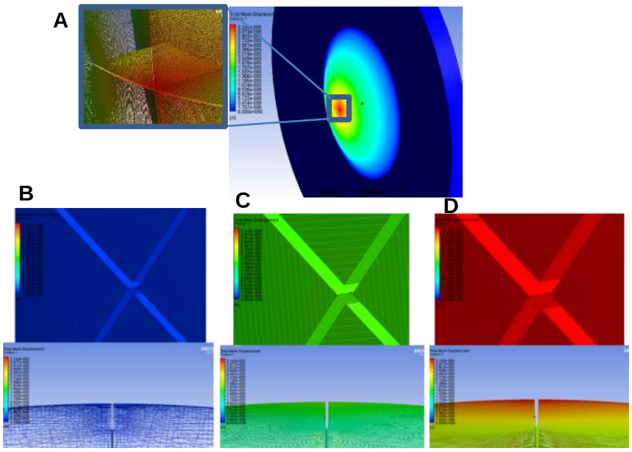

Fig. 5. Deformation of leaflets in response to pressure. (A) Distribution of the mesh deformation in the valve #1. Deformation of the leaflets at three different time steps, (A) t=0s, (B), t=0.5s, and (C) t=1s.

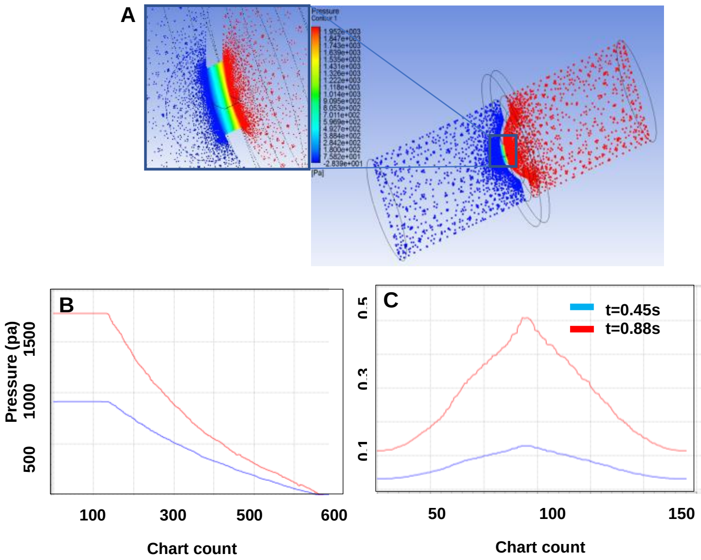

Fig. 6. Pressure change inside the fluid region. (A) Contour of pressure. (B) Pressure drop across central axis at t=0.45s and t=0.88s. (C) Pressure profile of the flow immediately after passing the gap across the line close to the leaflets, at t=0.45s and t=0.88s

The same analysis was performed for velocity and the corresponding contour is shown in Figure 7 (A). The velocity raises while the air passes through the gap and reaches the maximum value of $4.42m/s$. The velocity change across the central axis is shown in Figures 7 (B-D), at t=0.45s and t=0.88s. parameter to optimize the valve performance.

Figure 8 shows the results of experimental tests for five valves. Vacuum pump applied a harmonic pressure of $20 \sin(\pi t)$ to gain the milk. The pressure inside the bottle decreases gradually up P_{min} until the crosscut of the valve opened the air path, shown in Figure 8 (A). The pressure then raised up to P_{work}. At this point the inside pressure fluctuated around constant value and no pressure increment was observed. This condition was stable up to the end of the experiment. Results for each valve are shown in Figures 8 (B-F).

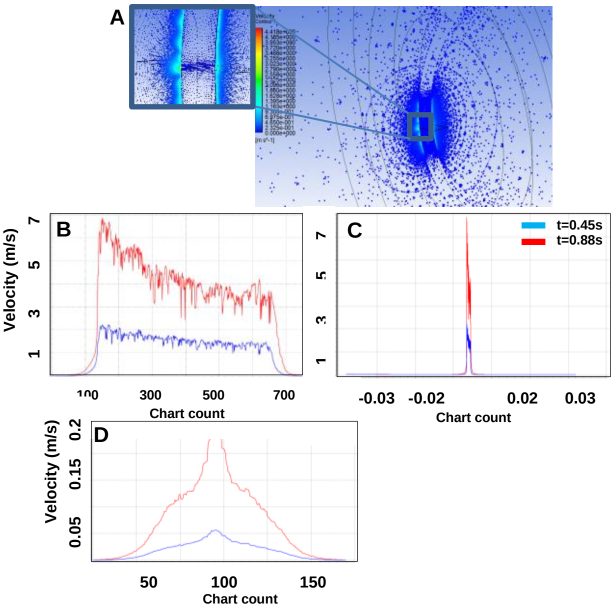

Fig. 7. Change of velocity inside the fluid region (A) Velocity contour. Change of velocity across the central axis, at t=0.45s and t=0.88s, where (B) central axis is divided by number of meshes, (C) central axis is divided by real length, and (D) immediately after passing the gap across the line close to the leaflets.

This experimental analysis is well matched with FEA computational analysis. Valve #4 with 1.5mm thickness, 8.5mm radius of curvature and 3.2mm crosscut has the highest V_{in} and fastest response to suction. It removes the inside vacuum faster and becomes stable in shorter time. Also, it keeps the inner pressure lower than other valves, which is more comfortable for infants feeding. It is worth mentioning that the longevity of the valve smust be tested under long time pressure performance. We will consider this as the next step of the study.

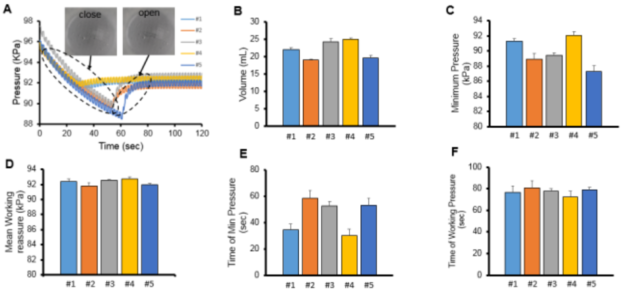

Fig. 8. Results of experimental tests for five valves. (A) Interior pressures. (B) Intake volume after two minutes. (C) Minimum pressure. (D) Minimum working pressure. (E) Time of minimum pressure. (F) Time of working pressure.

IV. CONCLUSIONS

This study presents a new technique to improve venting in nursing bottle. In this method, a self-adjustable venting valve is used to control the air flow inside the bottle. The air enters in the bottle through the valve and eliminates the interior partial vacuum. Any increment in liquid volume causes partial vacuum inside the bottle, and the valve responds to this pressure change and performs venting by opening the air pass. Experimental and computational analyses show that this venting valve system has a fast response to the suction pressure. The FSI simulation was limited to only one cycle of infant's actual suction. Also, the experimental results were obtained for only two minutes of experiment. Multi-cycles simulation and longer experiment must be performed for longevity of valves.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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Corresponding Author: Mohsen Akbari
Institute: University of Victoria
Street: 3800 Finnerty Road
City: Victoria
Country: Canada
Email: makbari@uvic.ca