Optimization of the India Mark II Hand Pump to create maximum cavitation for disinfection of water”

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ABSTRACT:

The India Mark II hand pump has been modified based on CFD analysis for creating cavitating conditions and is being used to disinfect water that passes and pumped through the pump. Cavitation is created through a restriction in the flow area opening as a function of lift of the check valve. When cavities collapse, they let out a high velocity microjet and a spherical shockwave that, if the former is incident on a cell wall of a microbe, will cause the cell wall to rupture and the microbe will be rendered unviable. Intensity of cavitation has been optimised in the hand pump to give a maximum disinfection.

The flow area opening as a function of lift was restricted by placing a ring of particular width over the check valve. Computational fluid dynamics simulations were used to optimize the dimensions of the ring. ANSYS 16.0 FLUENT was used to simulate the geometry of the India Mark II hand-pump. Simulations showed that the optimum level of cavitation occurred when lift is 60%, with instantaneous cavity collapse pressure of 401 atm. Experiments were carried out to validate the results at a pilot plant installed at ICT. Maximum disinfection of 92% was observed at ring width which gave 60% of flow area similar to that 60% predicted by simulations. Thus, experimental results corroborated the simulation predictions.

Key words: cavitation, microjet, disinfection, computational fluid dynamics simulations, ring, width.

1. INTRODUCTION

Cavitation was first discovered by Reynolds (1873) due to the unusual behaviour of boat propellers at high rotational speeds. Parsons (1906) improved upon Reynolds concept, recognized the role played by liquid vaporization in cavitation, and conducted the first experiments on cavitation.

Cavitation is a stochastic phenomenon and is defined as the inception, growth and adiabatic collapse of a partially or completely condensable gaseous or vapour cavity in liquid. Collapse of cavities result in very high temperatures and pressures, locally rising up to 9000K and 4000atm respectively. Tomita and Shima (1977) reported a maximum gas temperature of 8800K at the centre of the collapsing cavity. Cavitation occurs when pressure of the liquid falls below the vapour pressure of the liquid being subjected to flow. This can be seen using the equation of continuity and especially Bernoulli's theorem.

$$v = \frac{Q}{A} \tag{1}$$

Fluid continuity states that the flow rate at all points in a continuous flow is constant, and thus it can be seen that if the flow area decreases, the velocity will increase. As velocity increases pressure falls, and this can be shown using Bernoulli's theorem.

$$P_1 + \rho g h_1 + \frac{1}{2}\rho v_1^2 = P_2 + \rho g h_2 + \frac{1}{2}\rho v_2^2 \tag{2}$$

Since, the level of the liquid remains constant through a horizontal pipe, the assumption of $h_1=h_2$ can be made. Therefore,

$$P_1 + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 \tag{3}$$

Since the diameter of the constriction is much less than the diameter of the pipe, it is known that $v_1 << v_2$. Therefore, with this assumption we can approximate equation (2) to:

$$P_1 = P_2 + \frac{1}{2}\rho v_2^2 \quad (4)$$

Thus, as the velocity increases, the pressure decreases. This increases the chances for cavitation, denoted by the cavitation number σ, which is defined by:

$$\sigma = \frac{p_\infty - p_V(T_\infty)}{\frac{1}{2}\rho_L U_\infty^2} \quad (5)$$

Where U, P and T are reference velocity, pressure and temperature respectively. Thus, as the bulk pressure of the liquid reduces, the potential for cavitation becomes higher.

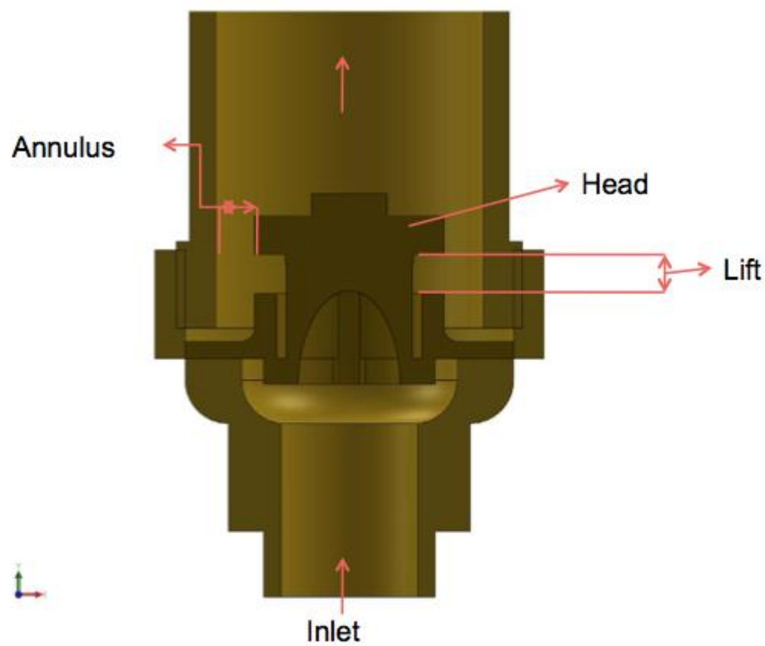


Figure 1

Thus, the percentage flow area opening as a function of lift (as shown in Fig. 1) was to be restricted using the above modified check valve. Intensity of cavitation measured by the collapse pressure was to be maximum at the optimum width of the ring. This is because when cavity collapse is strongly asymmetric, the dominant form of perturbation (Rayleigh-

Taylor instability) is a re-entrant jet, as shown in Fig. 2. Re-entrant jets were reported by Lauterborn and Bolle (1975) and Chapman and Plesset (1971) and Chahine (1977).

Figure 2: Re-entrant jet photographed by Crum et al (1998)

Along with a re-entrant jet, a spherical shock wave is also created during cavity collapse, which was reported by Herring (1941), Gilmore (1952), Hicking and Plesset (1963) and Sundaram et al 2003. If the re-entrant jet or the shockwave is incident on the microbial cell membrane present in liquid, the cell membrane disintegrates and renders the microbe unviable. Use of hydrodynamic cavitation for cell disruption was reported by Harrison (1990), Harrison and Pandit (1992), Save et al (1994 and 1997) and Balasundaram and Pandit (2001).

Previous work on cavitation in the India Mark II hand pump was carried out by Manchalwar et al 2015. The dimensions of the check valve were optimised to create maximum cavitation. In the present work, the dimensions of the check valve are constant, preventing the need of re-manufacturing check valves, and the width of a ring placed on top of the check valve is only changed and optimised to limit the liquid flow area resulting in cavitation.

Fig 3A: Original check valve

Fig 3B: Modified check valve

2. SIMULATION METHODOLOGY

In order to optimise the dimensions of the ring placed on the check valve, the percentage flow area opening as a function of lift that produced the maximum intensity of cavitation needed to be found. The modification and the original check valve is shown in Fig. 3B and Fig. 3A respectively.

A 2-D sketch of the cross section of the check valve in the hand pump was created on ANSYS DESIGNMODELER as shown below. The dimension V4 (vertical 4) represents the lift. Fig. 4 schematically shows the geometry in 2D.

Table No.1 below shows different configurations which were simulated numerically.

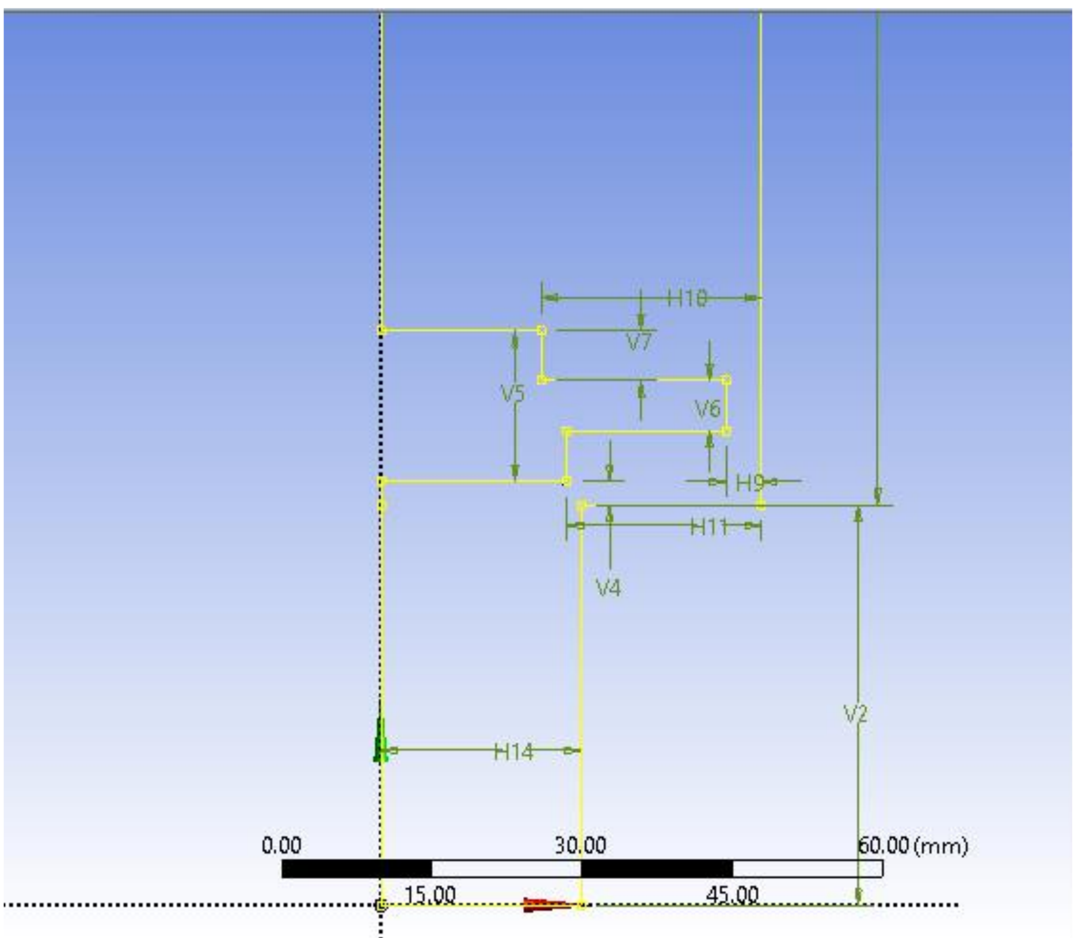


Fig 4: 2D geometry generated

Percentage flow are opening as a function of lift (%)	Height 'V4' (mm)
10	1.2
20	2.4
30	3.6
40	4.8
50	6.0
60	7.2
70	8.4
80	9.6
90	10.8
100	12.0

Simulation steps

The 2-D sketch was then revolved around the y-axis (vertical axis) to form a 3D cylindrical structure of the hand pump on ANSYS 16.0 DESIGNMODELER. For speed and ease of calculations, and quarter symmetry model was used with vertical faces along XY and YZ planes considered as Symmetry.

The geometry was meshed using ANSYS MESHING. Mesh metric was set to orthogonal quality. The wall of the cylinder, or the curved face was given a cell face sizing of 0.002m. For the inner faces, or symmetry walls, a cell face sizing of 0.0015m was applied. The Advanced Size function was set to 'ON PROXIMITY AND CURVATURE' so that the calculation would be accurate around the annulus of the check valve. The growth rate of the meshing cells was reduced from the Default 1.2 to 1.05, so as to prevent large growth of meshing cells as one moved inside the geometry. The meshed geometry was exported to ANSYS 16.0 FLUENT to solve for liquid properties. The model used to calculate liquid properties through the geometry was the REALIZABLE k-Ɛ MODEL. This was chosen because the flow of liquid through the geometry is turbulent, given by the Reynolds's number.

For turbulent flow *Re* is greater than 4000.

$$Re = \frac{dv\rho}{\mu}$$

Minimum velocity for the flow to be turbulent can be calculated through the following formula:

$$v = \frac{4000 \times \mu}{\rho \times d}$$

$$v = \frac{4000 \times 8.9 \times 10^{-4}}{1000 \times 0.076}$$

Since flow through the pump at the inlet is greater than $0.047 ms^{-1}$, the flow is assumed turbulent.

The use of REALIZABLE k-Ɛ model over the STANDARD k-Ɛ model is due to the improved transport equation of Ɛ and because C_μ is considered variable instead of constant. The transport equation for k is:

$$\frac{\partial}{\partial t}(pk) + \frac{\partial}{\partial x_j}(pku_j) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu t}{\sigma_k})\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k$$

And for Ɛ is:

$$\frac{\partial}{\partial t}(p\varepsilon) + \frac{\partial}{\partial x_j}(p\varepsilon u_j) = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S_\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{v\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon$$

Momentum balance and mass continuity is also considered in ANSYS 16.0 Fluent. Momentum balance is given by:

$$\frac{\partial}{\partial t}(\rho\overline{u}) + \nabla.(\rho\overline{u}\overline{u}) = -\nabla P - \nabla.(\rho\overline{u}'\overline{u}') + \mu\nabla^2\overline{u}_i + \rho\overline{g}$$

And mass continuity by:

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho\overline{u}) = 0$$

Boundary conditions were set to the following:

1. Inlet:

   Velocity: 3.1ms^{-1}. This was decided on the basis of typical water pumping rates obtained in India Mark II hand pump operating at 50 strokes per minute. Hydraulic diameter- 0.04m

2. Outlet:

   Hydraulic diameter- 0.076m

Solving methodologies were set at:

- Pressure- PRESTO!
- Momentum- Second Order Upwind
- Turbulent kinetic energy- Second Order Upwind
- Turbulent Kinetic Energy Dissipation Rate- Second Order Upwind

Extent of cavitation and collapse pressure could not be calculated solely based on bulk pressure drop due to the turbulent nature of the liquid. Local pressures in the centres of turbulent eddies can be lower than the bulk pressure of the liquid. Therefore, 20 massless particles were injected into the cylinder at the Cartesian coordinates of {0.035(x), 0.04(y), 0(z)} using the Discrete Phase Model (DPM). DPM is given by:

$$\frac{\partial u_P}{\partial t} = F_D\left(u - u_p\right) + \frac{g_x(\rho_P - \rho)}{\rho_P} + F_x$$

These particles mimic paths taken by cavities. Particle data of pressure at each instance of time was obtained and was used to solve the RAYLEIGH-PLESSET equation. The equation was solved using the Fourth Order Runge Kutta approximation method.

$$\frac{P_B(t) - P_\infty(t)}{\rho} = R\left(\frac{d^2R}{dt^2}\right) + \frac{3}{2}(\frac{dR}{dt})^2 + \frac{4\mu}{\rho R}\left(\frac{dR}{dt}\right) + \frac{2\sigma}{\rho R}$$

It is split into 2 simultaneous first order differential equations (equations 13 and 14):

$$R' = x$$

$$\frac{dx}{dt} = \frac{1}{R\rho}\left(P_B(t) - \frac{2\sigma}{R} - \frac{4x}{R} - P_\infty\right) - \frac{3}{2R}(x)^2$$

A typical cavity dynamic behavior (radius vs. time) is shown in Fig. 5

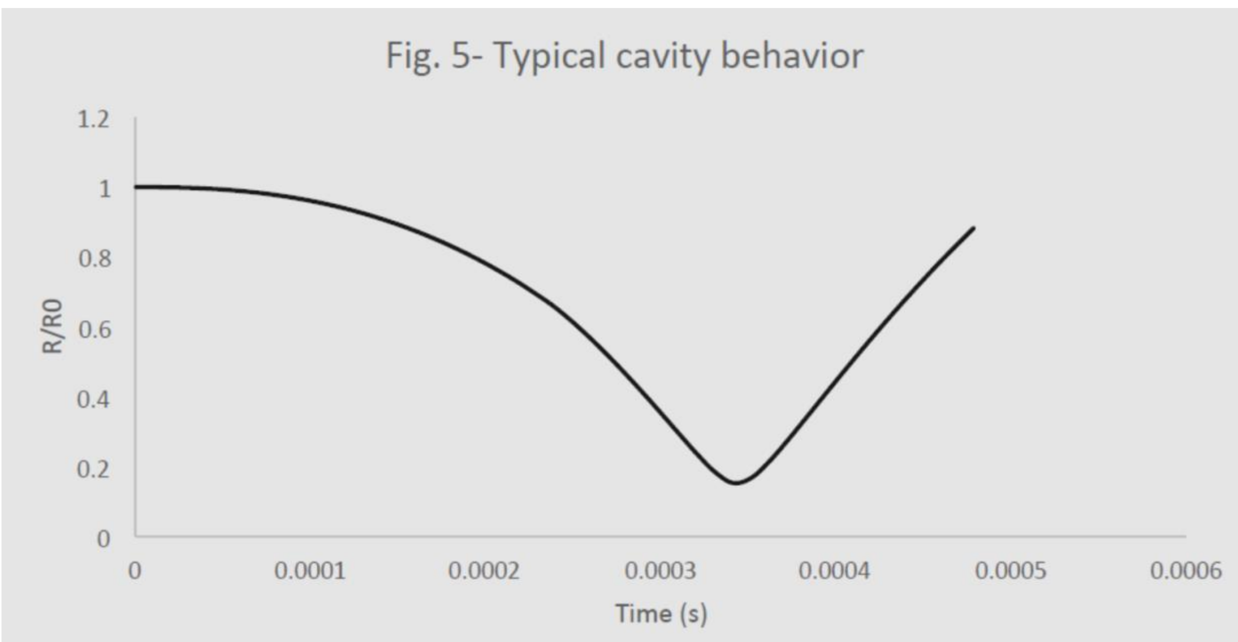


Figure 5 Typical Cavity behavior

3. EXPERIMENTAL METHODOLOGY

Equipment, Materials and Media used for the bacterial enumeration was as follows:

Equipment:

- Laminar air flow
- Micropipette- 1 ml and 0.1 ml
- Incubator at 37±1°C

Materials:

- Sterile 90mm Petri plates

Media:

- Plate count agar

Methods for CFU analysis:

As per the standard protocol water sample was spiked with fresh culture of E. coli. Before and after treatment sample was collected and was tested in the laboratory to check the efficacy of the treatment. The treatment consisted of pumping of the spiked water using different India Mark II modified hand pumps.

1. 24 hr. fresh culture of E. coli (ATCC 2346) with culture density 106 CFU/ml was prepared.
2. 100ml of the above culture was inoculated into 100L of raw water in a ground floor tank to get the final concentration of approximate 10^3 CFU/ml.
3. The culture was mixed properly in the raw water with the help of a big rod so that uniform mixing is obtained.
4. Spiked raw water (before treatment sample) was collected in a 200ml sterile bottle.

5. The water samples collected were brought to the laboratory in an ice box at 0°C to 4°C.
6. Serial dilutions were carried out, 1ml from each dilution was inoculated in the sterile petri dishes poured with sterile Plate Count Agar and plates were incubated at 37°C for 24 to 48 hr.
7. After completion of incubation, the colonies were counted for raw and treated water samples.
8. With the help of the following formula, % reduction is calculated.

$$\text{Percentage Reduction} = \frac{\text{Count in raw water sample} - \text{Count in treated water sample}}{\text{Count in raw water sample}} \times 100$$

Methods for obtaining after treatment sample of water:

Methods:

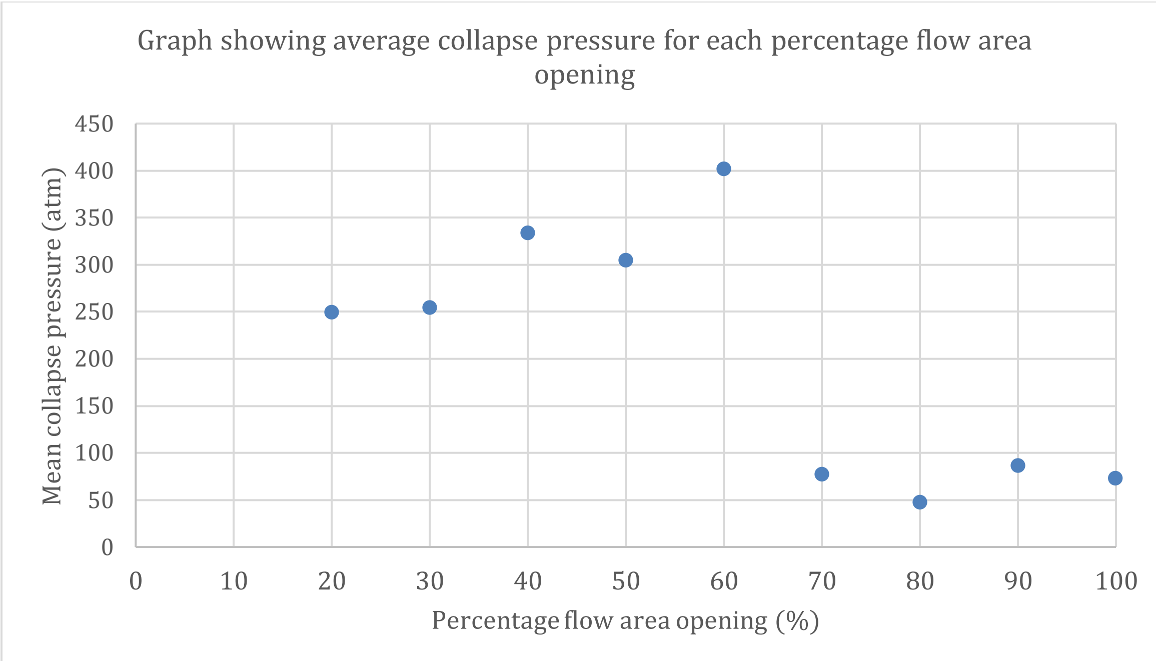
1. Water was collected from the pilot plant installed in ICT with pumping rates of 40 strokes, 50 strokes and 60 strokes per minute and was independently stored. The objective was to not only experimentally verify the results obtained in the simulations, but also to put together Standard Operating Procedure (SOP) to guide pump users on how to obtain maximum disinfection.
2. Four sample bottles were obtained. The original sample bottle was filled with the spiked water before passing the same through the pump. There would be a certain concentration of E.Coli bacteria in the original sample.
3. Then water was drawn from the pump and the first 10 liters of water were discarded. This is because water stagnancy would have caused the growth of microbes within the pump cylinder.

4. Then the experimental trials were conducted. For the experimenter handling and collecting samples in the sample bottle, it was imperative to wear gloves and use ethanol to kill all the microbes on the skin of the hands, or any part to be in contact with the water.
5. The handle of the hand pump was moved up and down 40 times in the course of a minute. After this duration, the water coming out of the pipe of the hand pump was collected using the “40 strokes” sample bottle.
6. The procedure was repeated for 50 strokes and 60 strokes per minute. CFU analysis was then carried out.

4. RESULTS AND DISCUSSION

The simulation results (numerical simulations of equations 7, 8, 9, 10, 11, 12, 13 and 14 for 20 independent cavities) are shown below in Table 2.

Percentage flow area opening (%)	**Mean Collapse pressure (atm.)**	**Maximum Collapse Pressure(atm.)**
20	249.38	1554.1
30	254.18	1839.8
40	333.91	2906
50	304.31	1733
60	401.86	2718
70	77.34	322.96
80	47.46	187.5
90	86.03	252.1
100	72.73	286.08



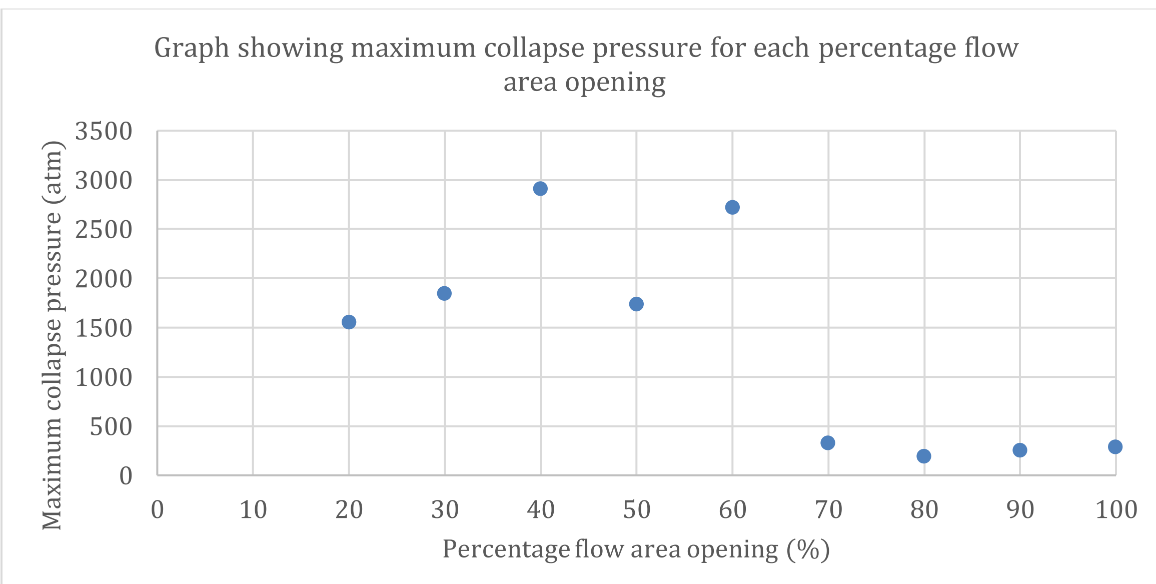


Fig. 6 and 7 above shows that 60% flow area opening as a function of lift, as the optimum dimension for the check valve, as it predicts the highest cavity mean collapse pressure of 401 atm. This can generate maximum cavitational shear to kill microbes present in water.

However, the maximum collapse pressure occurs at 40% flow area opening, with a value of 2906atm and thus may be suggested for use for the killing of more hardy microorganisms having tougher cell wall. Since optimum lift calculated is 60%, optimum ring dimensions could be estimated accordingly.

Samples	**No. of Strokes**	**Dilutions**				**CFU/ml**	**Percentage Disinfection**	**Average Disinfection**
		10	**100**	**1000**	**10000**			
Original	-	C*	C*	113	2	113000	-	-
With ring modification	40	C*	118	25	1	11800	89.56	**89.97**
		C*	112	18	0	11200	90.09	
		C*	110	C*	4	11000	90.27	
	50	C*	101	19	0	10100	91.06	**91.06**
		C*	103	10	1	10300	90.88	
		C*	99	13	3	9900	91.24	
	60	C*	75	26	2	7500	93.36	**91.24**
		C*	131	17	5	13100	88.41	
		C*	91	26	9	9100	91.95	

Therefore, it can be seen that the simulation results have been considered in the experimental protocol. It clearly shows that a maximum disinfection can be obtained at 60% flow area opening, whereas the numerical simulations indicate maximum mean cavity collapse pressure also at 60% flow area opening. Manchalwar et al 2015 reported disinfection from 85% to 92%. Disinfection obtained from the 60% flow area modification is close to the maximum disinfection reported by Manchalwar et al 2015. Also, this modification is cheaper to implement and easier to manufacture, as there is no requirement for the re-manufacturing of a check valve. More field trials need to be carried out to assess the locational effect of water quality.

Thus, it can be concluded that the computational fluid dynamics simulations were accurate in predicting the dimensions of the ring that generated maximum cavitational effects and thus maximum disinfection. For a single stage assembly, 91.24% of disinfection is highly desirable. It has also been reported that the strength and structural integrity of pathogenic cell walls is lower than that of the E. coli bacteria. Thus 91.24% disinfection would therefore allow for a much higher level of pathogenic disinfection that would result in less cases of water borne diseases in Indian villages.

Thus, it can be said that the Fourth Order Runge Kutta numerical solution technique for obtaining the solution of the governing equations was an acceptable approximation for the solution of the RAYLEIGH PLESSET equation and that the REALIZABLE k-Ɛ model was accurate in calculating the flows of liquid through a check valve geometry. It has also been proved that the cavitational shear created by the ring modification is effective in microbial disinfection.

CONCLUSIONS:

- Computational fluid dynamics simulations could accurately predict the occurrence and the intensity of cavitation occurring in the check valve of the India Mark II hand pump. This was validated by experimental results.

- Cavitation has micro-biocidal properties and spherical shockwave and high velocity micro-jet have the capacity to render microbes unviable.

- Optimum condition for disinfection was found to be 60% flow area opening as the function of the check valve. However, these dimensions may vary depending on the length of the lift and the water pumping rate (number of strokes).

- Pilot pant experimental results corroborated simulation results. Since cavitation is a stochastic phenomenon and it is proved it occurs within the India Mark II hand pump, further low pressure zones can be introduced to increase the probability of cavitation occurring. Thus, theoretically 100% disinfection can be achieved.

- The ring modification can be applied to hand pumps in villages to disinfect water to a 92% level. Since it is reported that the structural integrity of the cell wall of pathogenic microbial matter is lower than E.Coli, it can be stated that a large percentage of pathogenic matter will be killed.

NOMENCLATURE

Q	Flow rate
A	Area of flow
v, u	Fluid phase velocity
P	Pressure
ρ	Density
g	Acceleration due to gravity
Re	Reynolds number
μ	Dynamic viscosity
k	Turbulent kinetic energy
G_k	Generation of turbulent kinetic energy due to mean velocity gradients
G_b	Generation of turbulent kinetic energy due to buoyancy
σ_k	Turbulent Prandtl number for turbulent kinetic energy
ε	Turbulent kinetic energy dissipation rate
Y_M	Contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate
S_K	User-defined source term for turbulent kinetic energy
$C_{1\varepsilon}$, C_2	Constants
S_ε	User defined source term for turbulent kinetic energy dissipation rate
$\sigma\varepsilon$	Turbulent Prandtl number for turbulent kinetic energy dissipation rate
F_D	Drag force per unit cavity mass
F_x	Additional acceleration (force/unit cavity mass)
u_p	Cavity velocity

ρ_P	Cavity density
gx	Force of gravity on the cavity
$P_B(t)$	Pressure inside the cavity as a function of time
$\frac{dR}{dt}$	Rate of change of cavity radius
$P_\infty(t)$	Pressure infinitely far from the cavity as a function of time
σ	Surface tension of the cavity

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ACKNOWLEDGEMENTS:

One of the authors, Sankhe Sidharth would like thank the authorities of Institute of Chemical Technology, Mumbai for their constant support. He would also like to thank Gaurav Dastane for teaching him how to use ANSYS and always being there to help him.