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REVIEW

A comprehensive review of cavitation in valves: mechanical heart valves and control valves

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Abstract
Valves are widely used in various working conditions for their flow control functions, and the cavitation inside valves has been investigated owing to its harm to the valve itself and the connecting downstream parts. This paper presents a comprehensive review of the progress that has been achieved in the past years about cavitation in valves including both mechanical heart valves and control valves. The review is divided in the following parts, namely the location where there is a high possibility of the occurrence of cavitation, the parameters that affect cavitation intensity, and the methods to minimize cavitation intensity. It should be noticed that although simulation has been widely used, advanced experiments are still needed in order to obtain accurate analysis of cavitation in valves and the cavitation model still needs to be improved.

Keywords Cavitation · Mechanical heart valves · Control valves

Abbreviations

MMHVs	Monoleaflet mechanical heart valves
BMHVs	Bileaflet mechanical heart valves
BS valve	Björk–Shiley valve
CFD	Computational fluid dynamics
CM valve	CarboMedies valve
FSI	Fluid–structure interaction
LES	Large eddy simulation
MS	Minisac
VCO	Valve-covered orifice
CT	Computed tomography
RANS	Reynolds-averaged Navier–Stokes equations
SJM valve	St. Jude Medical valve

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Introduction

Valves including mechanical heart valves and control valves have been widely used in many applications. Mechanical heart valves are used to replace damaged heart valves to provide normal functions that are needed for human [1], and it can be treated as a kind of control valves, while control valves are mainly used in piping systems to regulate pressure [2, 3] and flow rate [4], or control the flow direction and open/close status [5], etc. For those valves, the safety and the longtime operation without breaking down during the operation are critical.

Some reviews about a certain control valve have been made in the past. Thorley [6] summarized the transient flow behavior of check valves. Petherick and Birk [7] did a literature search and review on the design, testing, and modeling of pressure relief valves. Abd Fatah et al. [8] presented the discussion of magnetorheological valves in the design configurations and mathematical modeling. There are more reviews about mechanical heart valves compared with control valves, and some of them were summarized by Zakaria et al. [1].

Cavitation is an important phenomenon in many occasions where there is a high flow velocity or high pressure drop with the liquid working fluid; it is common in valves and may cause vibration, noise, and damage. To now, cavitation has attracted many attentions in the fields concerning valves due to its harm to the systems.

Cavitation in hydraulic machinery has been reviewed in some studies. Luo et al. [9] discussed cavitation in pumps and turbopumps, and the development of the numerical models dealing with cavitation was also presented. Kumar and Saini [10] discussed cavitation in hydroturbines with theoretical, experimental, and analytical investigations, while Gohil and Saini [11] summarized the coalesced effect of cavitation and silt erosion in hydroturbines. Although lots of works have been done about cavitation in valves, the relative reviews have been rarely discussed before. Johansen et al. [12] did reviews about cavitation inside mechanical heart valves and the cavitation intensity was potentially related with the valve closing conditions and valve features, and they also summarized the techniques used to detect cavitation. For control valves, due to their various kinds and structures, there is no direct review about cavitation until now. Thus, in this paper, the recent progress of the study on cavitation in valves is emphasized and divided into two categories, namely cavitation in mechanical heart valves and cavitation in control valves.

Cavitation in mechanical heart valves

Mechanical heart valves are important for patients undergoing heart diseases, Andersen et al. [13] evaluated cavitation in patients with mechanical, biological, and native heart valves, and they found that cavitation only occurred in mechanical heart valves. When cavitation occurs, mechanical heart valves may suffer from high possibility of thromboembolic complications and blood cell damage. According to the structure of mechanical heart valves, they can be divided into two categories.

Cavitation in monoleaflet mechanical heart valves

Common monoleaflet mechanical heart valves (MMHVs) are shown in Fig. 1, and the literature on cavitation in MMHVs is summarized in Table 1. The closing dynamics of valve leaflet against the seat stop can be treated as two impinging rods approximately, it is found that both squeeze flow and water hammer phenomenon are basic factors for cavitation and erosion pits [14–16], and the onset of cavitation can be delayed and the cavitation intensity can be reduced by decreasing the contact areas and the squeeze flow velocity [15]. Moreover, cavitation intensity can also be reduced by improving valve design [17]. Besides, the closing velocity of valve disk [14] and the vortices in the vicinity of the valve tips [18] at the instant of valve closure affect the cavitation inception, and the onset of diastole and systolic is related to the cavitation intensity [19].

Cavitation pits mainly appear around the region of valve disk in contact with the valve stop [20, 21] and at the edge of major orifice region for MMHVs with stop [22]; the images of cavitation bubbles in the MMHVs are shown in Figs. 2 and 3. For Björk–Shiley Monostrut valves, Bachmann et al. [23] found that bubble cavitation occurred at the instant of valve closure due to the occluder rebounding and lasted on the order of 0.3 ms, while Kini et al. [24] found that cavitation lasted about 1 ~ 2 ms after the instant of valve closure, and the variation in cavitation bubbles under different times after valve closure is shown in Fig. 4.

The valve holder flexibility does not affect the cavitation inception, but when the loading rates are the same at the instant of valve closure, cavitation bubbles will not appear in valves if the leaflets are flexible or there is no valve stop in the major orifice zone of valves [25]. Higher heart rate [26], higher pressure drop [20, 21], or larger valve size [25] will increase the cavitation incidence. When there exists CO_2, the cavitation intensity will not be affected, but the stability of bubble growth is affected [27]. As for the detection of cavitation in mechanical heart valves, Herbertson et al. [28] found that the valve-induced cavitation could be investigated by the wavelets analysis, and Takiura et al. [29, 30] found that the OH radicals caused by cavitation may result in the faint light which could be used to analyze the collapse of cavitation bubbles.

Cavitation in bileaflet mechanical heart valves

The comparison between monoleaflet and bileaflet mechanical heart valves has been made [31–33]. The common bileaflet mechanical heart valves (BMHVs) are shown in Fig. 5, it is found that the formation of cavitation results from

(a) Medtronic Hall valve **(b)** Björk–Shiley valve **(c)** Omnocarbon valve

Fig. 1 Common monoleaflet mechanical heart valves [32]

Table 1 Literature on cavitation in MMHVs

References	Type of MMHVs	Valve size	Boundary conditions	Focusing
Zapanta et al. [26]	Björk–Shiley Monostrut valve	25 mm, 27 mm		
Lee et al. [22]	Medtronic Hall valve	27 mm, 29 mm	Loading rate: 705, 1500, 3000 mm Hg/s	Loading rate; structure of the valves
Kini et al. [24]	Björk–Shiley Monostrut valve	27 mm	Atrial chamber is held open to atmosphere; ventricular chamber: different pressures and the peak value is 120 mm Hg	The effects of occluder rebound
Bachmann et al. [23]	Björk–Shiley Monostrut valve		Pump: 70 bpm, systolic duration: 300 ms, peak systolic ventricular pressures: 125, 150, 175 mmHg	To find out the bubble formation mechanism
Johansen et al. [38]	Björk–Shiley Monostrut valve, Medtronic Hall valve	29 mm	Heart rate: 60–170 bpm; systolic duration: 20–400 ms	Using non-deterministic part of the high-frequency pressure fluctuations to evaluate cavitation
Lim et al. [15]	Treat MMHVs as two impinging rods	Stationary rod: 34 mm, movable rod: 9.5 mm	Input pressure: 2.5, 5, 7.5, 10, 15 and 20 N/m^2	Impact velocities; contact areas; squeeze flow velocity
Takiura et al. [29, 30]	Björk–Shiley valve	20 mm	Heart rate: 60–100 bpm; pressure difference exerted on the MHV: 150 mm Hg	The faint light emission
Eichler and Reul [33]	Björk–Shiley Convexo Concave (BSCC), Medtronic Hall (MH)	BSCC-19 MH-27		Fluid density; fluid viscosity; valve deign; temperature
Lee et al. [32]	Medtronic Hall valve, Björk–Shiley valve, Omnocarbon valve	21 mm, 23 mm, 25 mm	Heart rates: 60–100 bpm	Mechanism of mechanical heart valve cavitation
Lukic et al. [19]	Björk–Shiley valve		Mean arterial pressure was maintained at approximately 75 mm Hg with diastolic and systolic pressures of 60 to 90 mmHg	Systolic duration; diastolic duration
Herbertson et al. [27]	Björk–Shiley Monostrut valve, Medtronic Hall valve	29 mm	Loading rate: 500, 2500 and 4500 mm Hg/s	The role of CO_2 in MHV-induced cavitation bubble formation
Herbertson et al. [28]	Medtronic Hall valve	29 mm	Loading rate: 500, 2500, 4500 mm Hg/s; heart Rate: 90 bpm; systolic duration of 300 ms	Apply wavelet denoising method to analyze cavitation in mechanical heart valves
Lee and Taenaka [31]	Medtronic Hall valve, Björk–Shiley valve, Omnocarbon valve	21 mm, 23 mm, 25 mm	Heart rates: 60–100 bpm	Mechanism of mechanical heart valve cavitation

Table 1 continued

References	Type of MMHVs	Valve size	Boundary conditions	Focusing
Lee et al. [20]	Medtronic Hall valve	23 mm	Heart rates: 60–90 bpm	The driving pressure
Lo et al. [17]	Medtronic Hall Standard; Medtronic Hall D-16; Omni Carbon	29 mm	Accelerated pulse rate: 600 bpm, transvalvular pressure: 120 mm Hg	Valve design
Lee et al. [21]	Medtronic Hall valve	23 mm; 25 mm	Heart rate: 80 bpm; 120 bpm	Estimating the MHV cavitation intensity using the slope of the driving pressure just before valve closure in electrohydraulic total artificial heart
Lo et al. [16]	Treat MMHVs as two impinging rods	Stationary rod: 5, 10, 24 mm, movable rod: 5, 10 mm	Different rod impact velocities: ~0.46–1.67 m/s	Impact velocities; contact areas

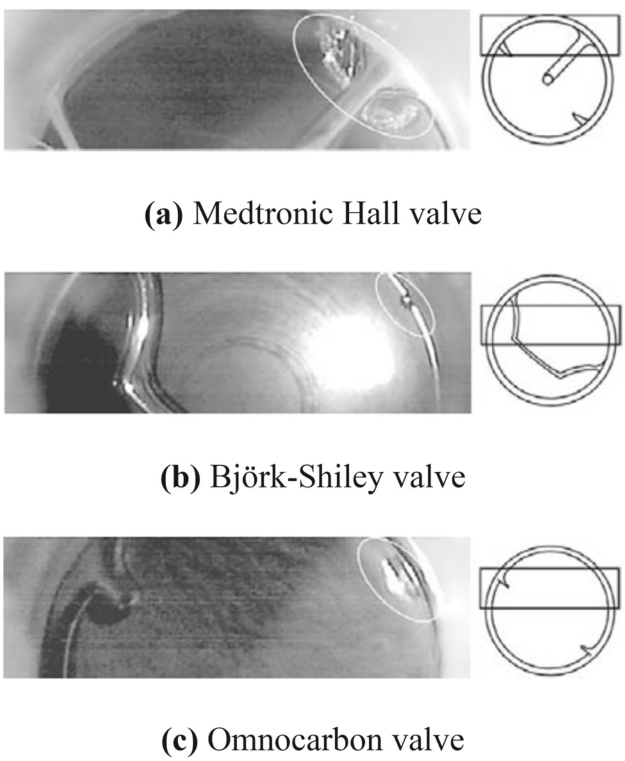


Fig. 2 Distribution of cavitation bubbles in MMHVs [31]

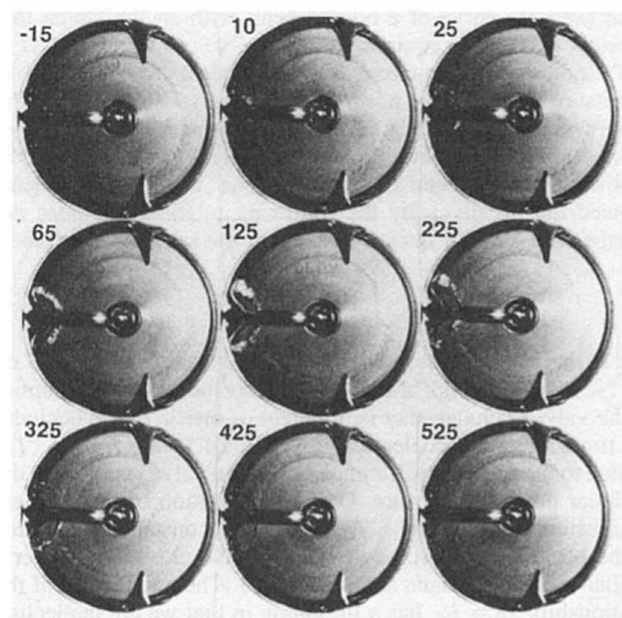


Fig. 3 Transient cavitation bubbles in Medtronic Hall valve [22]

the squeeze flow, and cavitation formation is related to the valve closing velocity, the geometry of valve leaflet, the valve design, and valve location [31, 32]. With the increase in the valve closing velocity, the valve stop area, and the valve size, the possibility of cavitation occurrence also increases, while the fluid density, the fluid viscosity, and the temperature have negligible effects on cavitation onset [31–33]. Besides, cavitation bubbles density in monoleaflet valves is higher than in bileaflet valves [32], and cavitation bubbles concentrate on the valve stop and along leaflet tip [31]; the cavitation bubble distribution under different mechanical heart valves is shown in Fig. 6.

As summarized in Table 2, Lee et al. [34] also found that the formation of cavitation bubbles could be contributed by squeeze flow for ATS, St. Jude Medical (SJM), and Björk–Shiley (BS) valves, and the cavitation bubbles under different BMHVs are shown in Fig. 7. Li et al. [35] found that the formed large scale vortices during the instant of valve closure and subsequent occluder rebound played a minor role in the formation of cavitation in SJM valves. Mohammadi et al. [36] found that the water hammer pressure due to cavitation played an important role in the crack propagation of the leaflets in SJM valves. Between SJM and CarboMedies

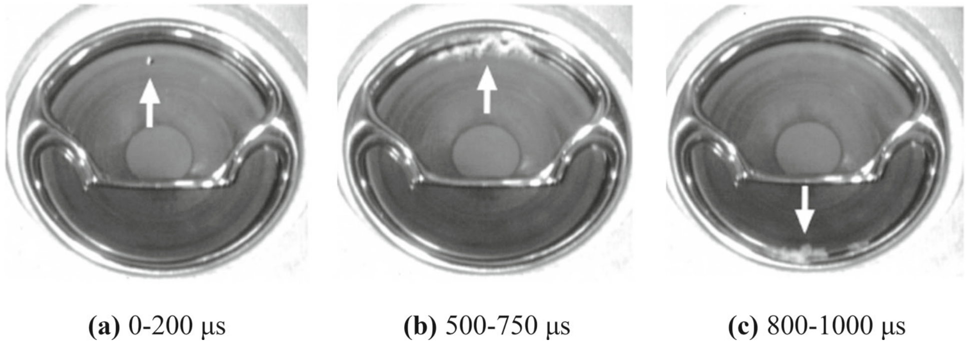


Fig. 4 Variation in cavitation bubbles under different times after valve closure in Björk–Shiley valve [30]

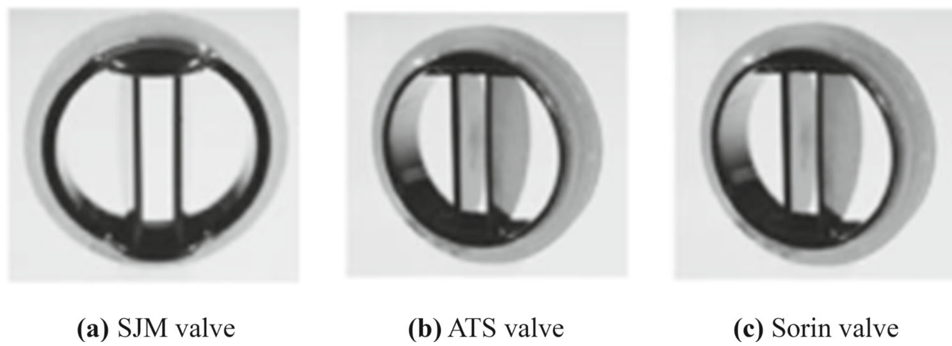


Fig. 5 Common bileaflet mechanical heart valves [32]

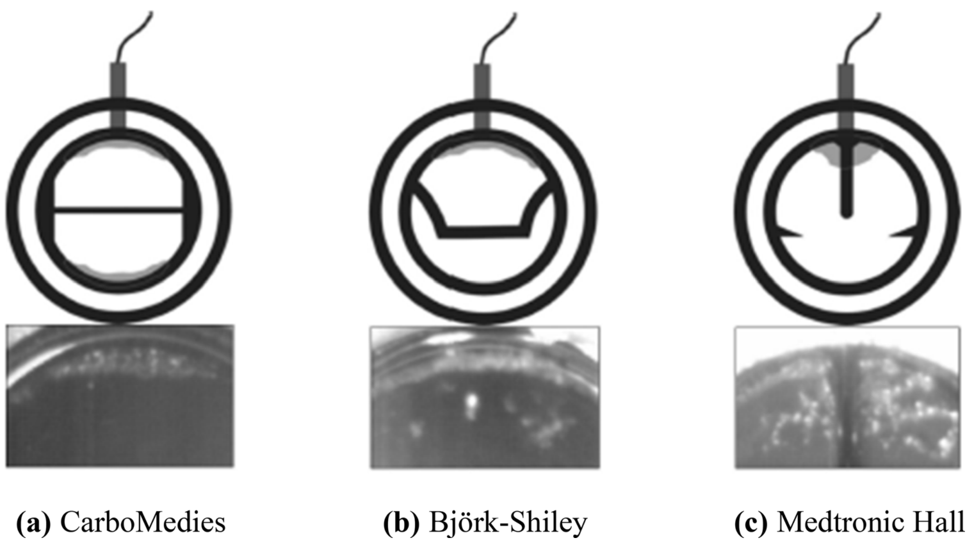


Fig. 6 Cavitation bubbles distribution under different mechanical heart valves [38]

(CM) valves, cavitation is most likely caused by the closure of the second leaflet [37].

Meanwhile, high-frequency pressure fluctuations will induce cavitation during the valve closure, and the isolated non-deterministic part can be used to evaluate and quantify cavitation due to its minimal information loss [12, 38]. Transient pressure signals at the time of leaflet/housing impact can be used as an indirect indication of the occurrence of cavitation, and the time–frequency analysis of the transient pressure signals can be applied to discriminate cavitation intensity [39–42].

Cavitation in control valves

Control valves are widely applied in numerous industries, and cavitation often appears in many kinds of control valves during the actual operation process. Dimensionless cavitation number or cavitation index is always used as a judgment to evaluate the proneness to cavitation.

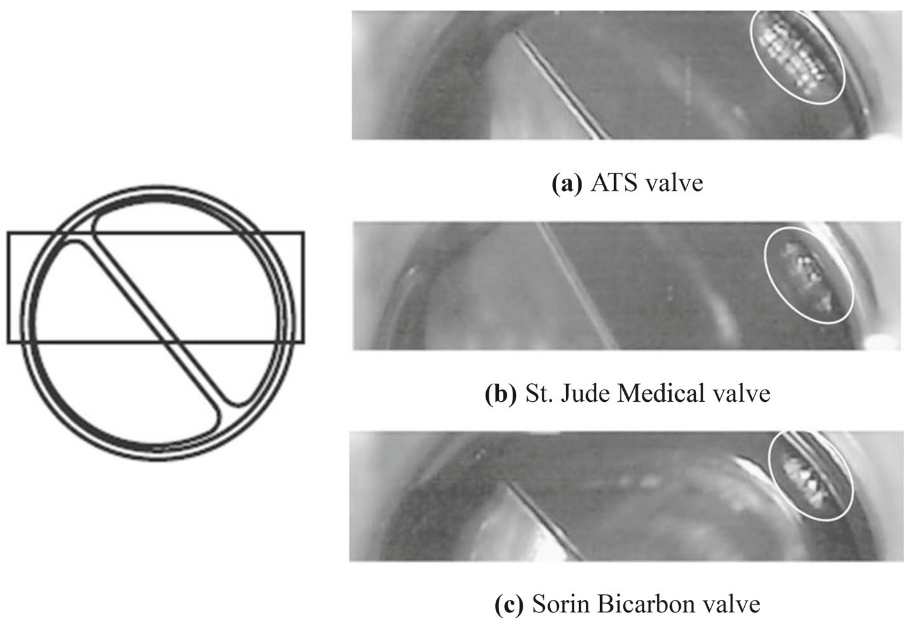
$$\sigma = \frac{p - p_{\mathrm{v}}}{1/2\rho v^2} \tag{1}$$

$$\sigma_{\mathrm{v}} = \frac{p_{\mathrm{u}} - p_{\mathrm{v}}}{p_{\mathrm{u}} - p_{\mathrm{d}}} \tag{2}$$

Table 2 Literature on cavitation in BMHVs

References	Type of MMHVs	Valve size	Boundary conditions	Focusing
Wu et al. [42]	St. Jude Medical valve, CarboMedics	31 mm	Heart rate: 70, 90, 120, 140 bpm	Transient pressure signals
Yu et al. [41]	Edwards Duromedics	29 mm	Driving pressure: 100–1300 mm Hg	Transient pressure signals
Dexter et al. [39]	CarboMedics	27 mm	In vivo	Transient negative pressure spikes
Wu et al. [40]	St. Jude Medical valve	25 mm	Heart rate: 300–1000 bpm	Transient pressure drop
Andersen et al. [13]	St. Jude Medical valve, Carpentier-Edwards pericardial bioprosthesis, coronary artery bypass surgery		In vivo	Evaluate cavitation in patients
Lee et al. [34]	ATS valve, St. Jude valve, Sorin Bicarbon valve	21 mm	Heart rate: 60–100 bpm	The possibility of using the bileaflet valves in an electrohydraulic total artificial heart (EHTAH)
Mohammadi et al. [36]	St. Jude Medical valve	30 mm	The aortic pressure: 80–120 mm Hg	Crack propagation in the leaflets
Li et al. [35]	St. Jude Medical valve	25 mm	Heart rate: 70, 90, 120 bpm	Vortex, tangential velocity, relative pressure drop
Johansen et al. [37]	St. Jude Medical, CarboMedics		In vivo	Evaluate cavitation in patients

Fig. 7 Cavitation bubbles under different BMHVs [34]



where σ is cavitation number, p_v is the saturated vapor pressure, ρ is the fluid density, p and v are the pressure and velocity at a reference location. σ_v is cavitation index, p_u is the upstream pressure of valves, and p_d is the downstream pressure of valves.

In the last decades, the numerical simulation has been made a great process and its application in cavitation in control valves has been discussed and verified. Adamkowski and Lewandowski [43, 44] validated the new single-zone discrete vapor cavity model in water hammer accompany with column separation resulted from the butterfly valves sudden closing. Couzinet et al. [45] proved the cavitation model proposed by Singhal et al. could be used to predict the discharge coefficient in safety relief valves when there was cavitation. Hong and Kim [46] found that compared with the Reynolds equation, the computational fluid dynamics (CFD) using Navier–Stokes equation was more sufficient to calculate lateral forces in spool valves. Longhitano et al. [47] found that the full cavitation model proposed by Singhal et al. together with large eddy simulation (LES) model had more

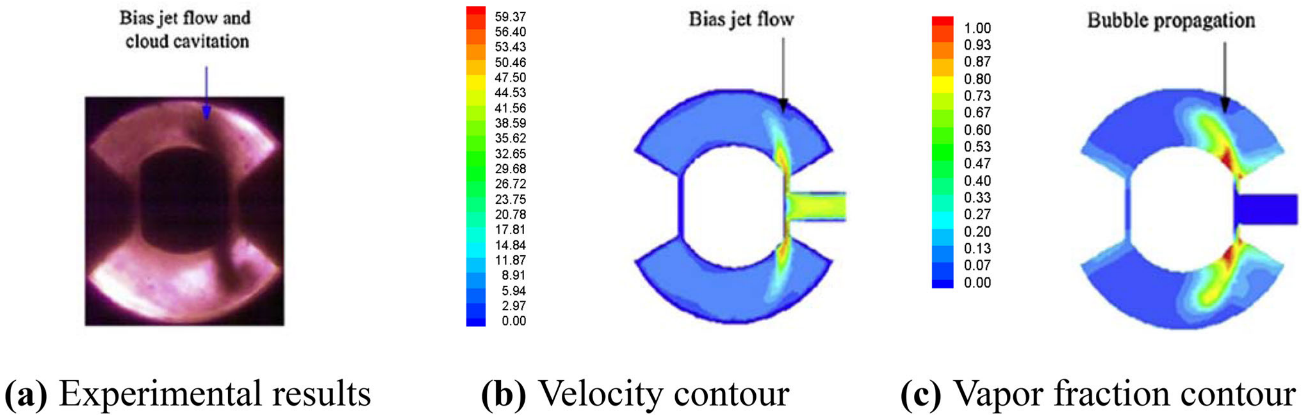


Fig. 8 Cavitation in the flapper–nozzle pilot stage under $Re = 1700$ [53]

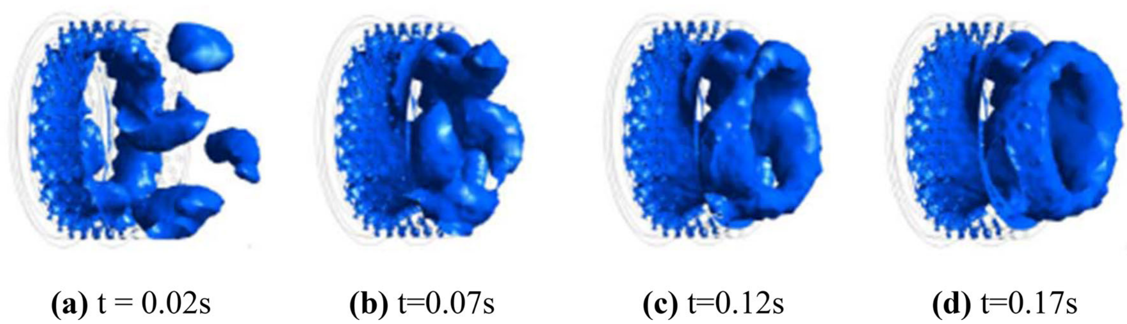


Fig. 9 Evolution of cavitation in the pressure regulating valves [54]

advantages than the standard two-equation turbulence model in terms of the prediction of transient behavior.

With the developments of measurement techniques and numerical methods, the flow mechanisms, geometrical optimization, and parameters that affect cavitation or affected by cavitation have been investigated.

The occurrence of cavitation in valves

Basically, the location where cavitation bubbles form varies in different control valves. In hollow jet valve, typical cavitating vortices appear as circular bubble chains near the valve needle due to the vortex motion in shear layer flow [48], and the cavitation damage has two patterns: One is big plastic crater with a fan-shaped wake and the other is irregular brittle pit [49]. In throttle valves, cavitation initially occurs close to the throttle orifice, and then, the circulating bubbles cluster formed [50]. Cavitation mainly appears on the valve rod top, the corners of the valve seat and channel [50, 51]. Washio et al. [52] found that in poppet valves, the flow separation at the edge of the valve seat and the solid contact between the seat and the poppet were two possible ways to generate cavitation nuclei. Li et al. [53] experimentally and numerically observed that in the flapper–nozzle pilot stage of electrohydraulic servo-valve, the onset of cavitation could be found at the leading edge of flapper and the inner and outer wall tip of nozzles; there was also cloud-like cavitation with jet flow between nozzle and flapper (Fig. 8). In pressure regulating valves, cavitation vapor emerges at the inlet of holes firstly. As the inlet pressure decreases, cavitation vapor fills the zone connecting the wall of the hole. Meanwhile, cavities scatter and distribute in several parts firstly, and then, a large annular cavity close to holes stretch and combine downstream (Fig. 9) [54]. Saito et al. [55] found in high-pressure cage type valves a couple of bubbles formed at a low opening and died out in a short distance away from the port. In minisac (MS) and valve-covered orifice (VCO) nozzles, the needle passage may suffer from cavitation if the needle is closed fast, and the slow closing velocity of the needle can make cavitation collapse at the end of injection [56]. For spool valves with flow-in and flow-out cases, the pressure drop at the throttling region is higher in flow-in cases and cavitation occurs more easily [57]. Zheng et al. [58] found that in coal oil slurry valves, cavitation mainly appeared at the downstream of the valve spool and cavitation erosion mainly appeared at the top of the valve spool (Fig. 10). Carlson found that compared with globe and control ball valves, standard ball valves and butterfly valves had a high proneness to cavitation [59].

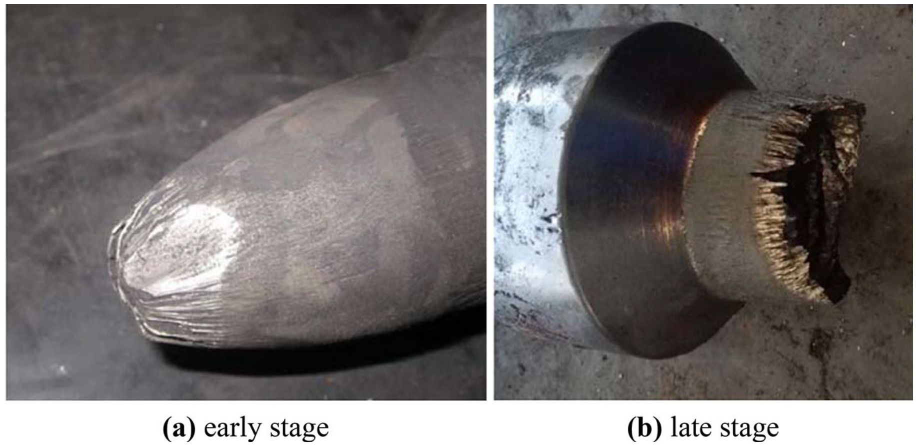


Fig. 10 Damage of valve spool in coal oil slurry valves at different stages [58]

Table 3 Literature focusing on the parameters that affect cavitation in control valves

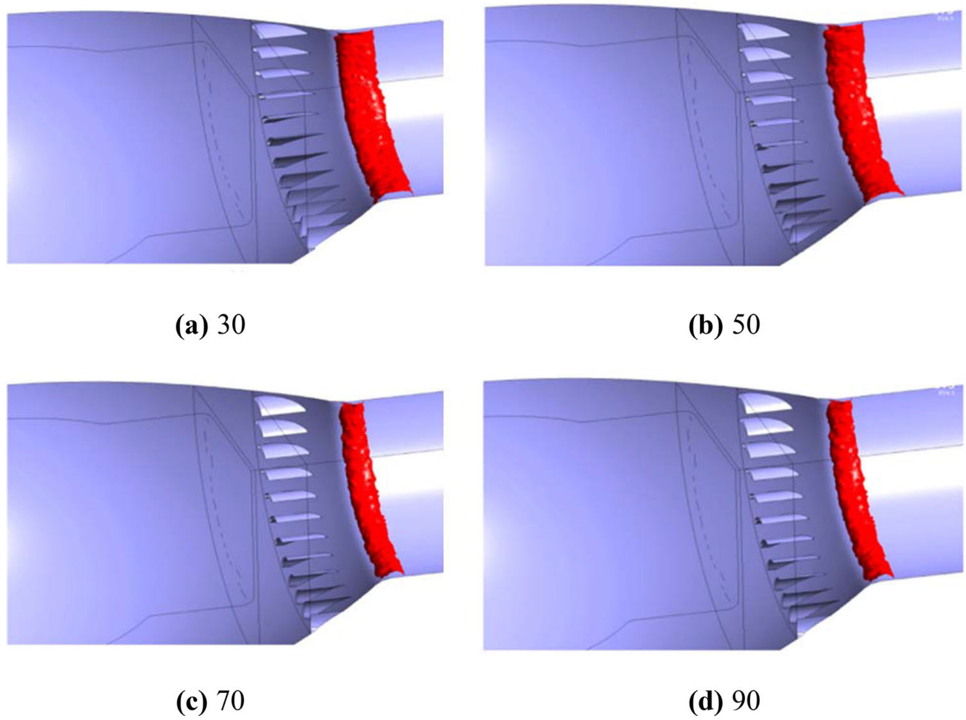
References	Valve type	Working fluid	Methods	Turbulence model
Yuzawa et al. [79]	Contoured plug valve	Water	Experiments	–
Nie et al. [66]	Two-stage throttle valve	Water	FLUENT	RNG $k–\varepsilon$
Gao et al. [77]	Poppet valve	Mineral oil	Singhal et al. model [60]	RNG $k–\varepsilon$
Bernad et al. [74]	Poppet valve	Water	Singhal et al. model	RNG $k–\varepsilon$
Gavaises [67]	Valve-covered orifice	Water	Experiments + Eulerian − Lagrangian cavitation model	Standard $k–\varepsilon$
Zou et al. [82]	Spool valve	Hydraulic oil	Experiments + FLUENT (Rayleigh–Plesset)	$k–\varepsilon$
Liu and Ji [71]	Rotary valve	Oil	CFD (FLUENT)	Standard $k–\varepsilon$
Du et al. [64]	Throttling valve	Oil	Experiments	–
Gholami et al. [63]	Needle-type control valve	Water	Singhal et al. model	Standard $k–\varepsilon$
Ko and Song [68]	Solenoid valve	Brake oil	Singhal et al. model	Standard $k–\varepsilon$
Ou et al. [73]	Pressure relief valve	In coal liquefaction	Schnerr–Sauer model [61]	RNG $k–\varepsilon$
Ou et al. [80]	Pressure relief valve	In coal liquefaction	Schnerr–Sauer model	RNG $k–\varepsilon$
Lee et al. [69]	3-way reversing globe valve	Water	CFX (Rayleigh–Plesset equation)	SST $k–\omega$
Wang et al. [76]	Control valve	Diesel	Schnerr–Sauer model	Realizable $k–\varepsilon$
Zheng et al. [72]	High-pressure differential control valve	Liquefied oil	Singhal et al. model	RNG $k–\varepsilon$
Liang et al. [75]	Poppet valve	Water	Schnerr–Sauer model	Realizable $k–\varepsilon$
Qian et al. [78]	Pilot control globe valve	Water	Schnerr–Sauer model	RNG $k–\varepsilon$
Han et al. [65]	Poppet valve	Water	Zwart–Gerber–Belamri model [62]	Realizable $k–\varepsilon$
Liu et al. [81]	Butterfly valve	Water with particle	Schnerr–Sauer model	Standard $k–\varepsilon$
Jin et al. [70]	Globe valve	Water	Zwart–Gerber–Belamri model	Realizable $k–\varepsilon$

Parameters that affect cavitation

Cavitation in control valves can be affected by the structural parameters, the valve opening, and the boundaries conditions, etc. Table 3 presents the literature focusing on the parameters that affect cavitation in control valves.

In needle-type control valves, cavitation intensity decreases with the increasing vane camber angle (Fig. 11) [63]. In throttle valves, the notch configuration has an influence on the cavitation distribution. As the groove depth increases, the inception of cavitation bubbles shifts to the left comer from the outlet comer of the groove (Fig. 12) [64]; as the cone angle increases, the cavitation intensity increases [65]. For the two-stage throttle valve, the passage area ratio should be set appropriately to improve the anti-cavitation ability [66], and the occurrence of cavitation can be suppressed compared with single-stage throttle valves [65]. Gavaises [67] found that for valve-covered orifice nozzles, the formation of geometric cavitation could be suppressed with tapered holes, but the formation of string cavitation

Fig. 11 Cavitation inside needle-type control valves with different vane angles [63]



could be enhanced using grooved needle (Fig. 13). Ko and Song [68] found for a solenoid valve a large ratio between the narrowest gap and the inlet area, and a small narrow gap length should be used to reduce vapor volume fraction. Lee et al. [69] conducted numerical simulations for 3-way reversing globe valve, and their results showed that cavitation intensity decreased with the increase in the tail length and the waist length. Jin et al. [70] found that in globe valves, large bending radius, large deviation distance, and large arc curvature linked to in/export parts could reduce the occurrence of cavitation (Fig. 14). Liu and Ji [71] pointed out for a rotary valve, the cavitation intensity increased with the decrease in the entry caliber, and appropriate groove depth should be chosen. Moreover, control valves with rounded edge, appropriate seal cone angle, and inverted cone hole have better anti-cavitation ability [76].

The increasing inlet pressure can increase the cavitation intensity in high-pressure differential control valves [72], pressure relief valves [73], butterfly valves [81], and poppet valves [74]. The amplitude and the frequency of inlet pressure also have great influence in poppet valves, when there is no groove at the valve port, the occurrence of cavitation can be suppressed with an increased frequency, and cavitation intensity can be enhanced with a decreased frequency [75]. Cavitation intensity increases with the increase in flow velocity in control valves [76], poppet valves [77], and pilot control globe valves (Fig. 15) [78]. High back pressure would be beneficial for the anti-cavitation ability in two-stage throttle valves [65, 66], poppet valves [77], contoured plug valves [79], and pressure relief valves [80]. However, high oxygen amount [79] and temperature [72] also increase the cavitation intensity.

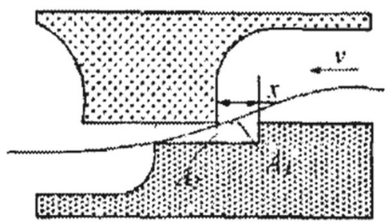
At small valve opening, cavitation occurs near valve seat, but cavitation mainly appears at the downside of valve disk under large valve opening and large velocity in globe valves (Fig. 16) [89]. With the increase in valve opening, the cavitation zone in front of the valve disk in pressure relief valves decreases [80] and cavitation intensity decreases in pilot control globe valves [78], butterfly valves [81], and high-pressure differential control valves [72], while the cavitation intensity is more violent with a deeper depth of groove and a larger valve opening inside the non-circular opening spool valve with U-grooves (Fig. 17) [82].

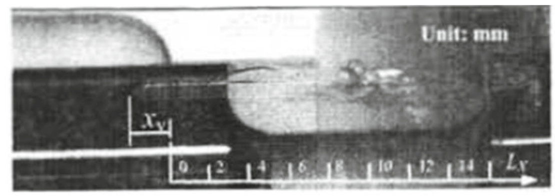
The effects of cavitation on other parameters

The occurrence of cavitation in valves not only has influences on other valve characteristics but also may have influences on vibration and noise, etc. The literature on the parameters that affected by cavitation is shown in Table 4.

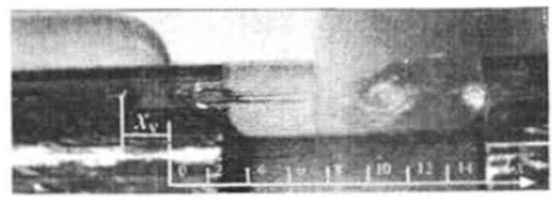
The discharge coefficient is higher when cavitation occurs in safety relief valves [85], and the valve flow coefficient diminishes as the occurrence of cavitation in 4/3 proportional directional valves [86], and cavitation index, loss coefficient, and the recirculation length behind ball valves increase with the decreasing ball valve opening [87, 88]. Ferrari and Leutwyler [89] found that in globe valves, cavitation did not increase the transverse force but acted as a limiter, while the

Fig. 12 Cavitation in throttle valves with different groove depths [64]

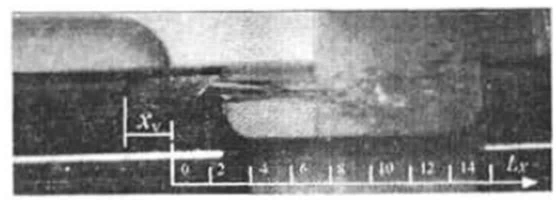




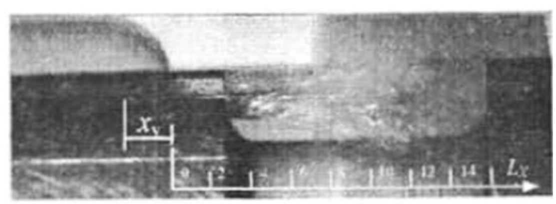
(a) U01,v ≈ 72.5 m/s



(b) U02, v ≈ 47.5 m/s



(c) U03, v ≈ 36.1 m/s



(d) U04, v ≈ 32.9 m/s

effects of cavitation on the axial force were complex, and the cavitating flow in conical relief valves affected the thrust on poppet and poppet lift [90]. Caillaud et al. [91] found that cavitation reduction in globe-style valves did not affect the low-frequency excitation and could not reduce the pipe vibration, while the generation and exploration of cavitation bubbles could cause the vibration increase significantly in poppet valves [74].

Bernad et al. [74] found that the noise in poppet valves would be elevated due to the exploration of cavitation bubbles and the formation of vapor plume. Okita et al. [92] found the fluctuation of cavitation volume was corresponding to the downstream fluctuation of pressure, and with the decrease in cavitation number, the peak values of pressure fluctuation diminished as the peak frequency increased. The cavitation in hydraulic relief valves could be a cause of the valve noise. Yi et al. [90] also found that in conical relief valves, the augmented noise under unstable state mainly resulted from the intensification of cavitation noise. Zou et al. [82] found that in spool valves, the acoustic noise level increased with the decreasing cavitation number if cavitation number was larger than 0.4, or acoustic noise would decrease with decreasing cavitation number.

Measurement of cavitation

Osterman et al. [93] compared visualization method with the measurement of pressure oscillations by the hydrophone in the determination of incipient cavitation, and they found that the visualization method was more efficient due to its sensitivity to cavitation. Brett et al. [94] visualized cavitation in a poppet valve with 3D X-ray computed tomography (CT) imaging, and they found that the simulated cavitation using CFD was similar to the 3D CT results. Jazi and Rahimzadeh

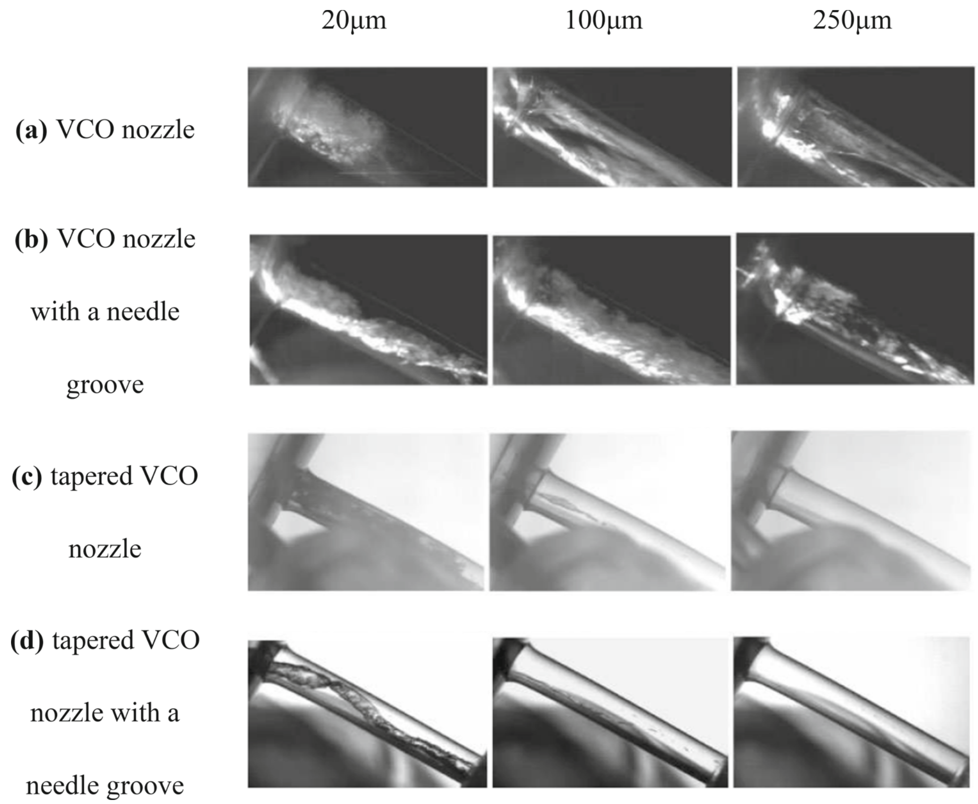


Fig. 13 Sample representative images of cavitation structures formed in the injection hole of the various nozzle designs [67]

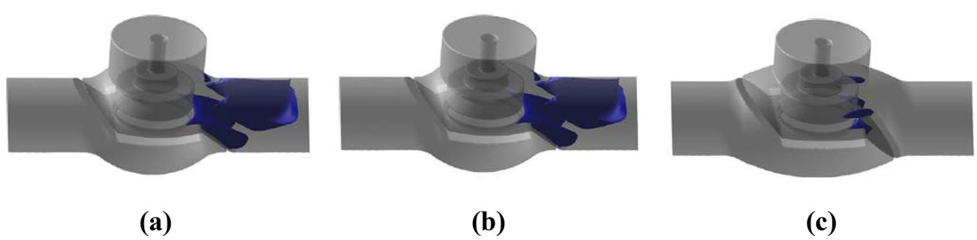


Fig. 14 Cavitation in globe valves with different bending radii [70]

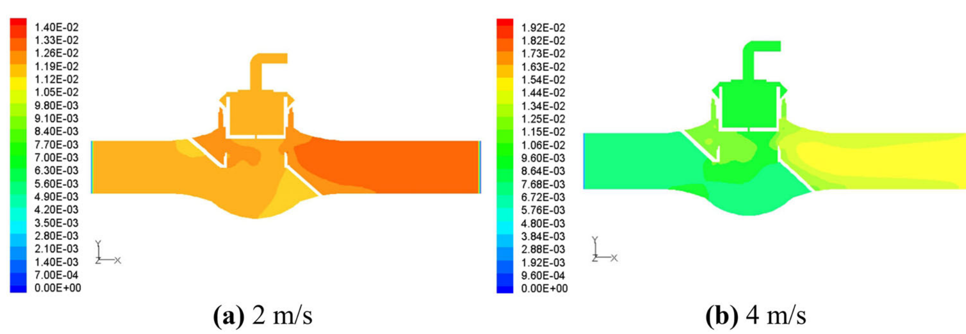
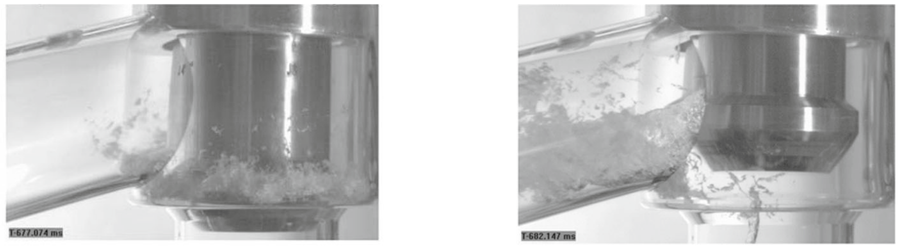


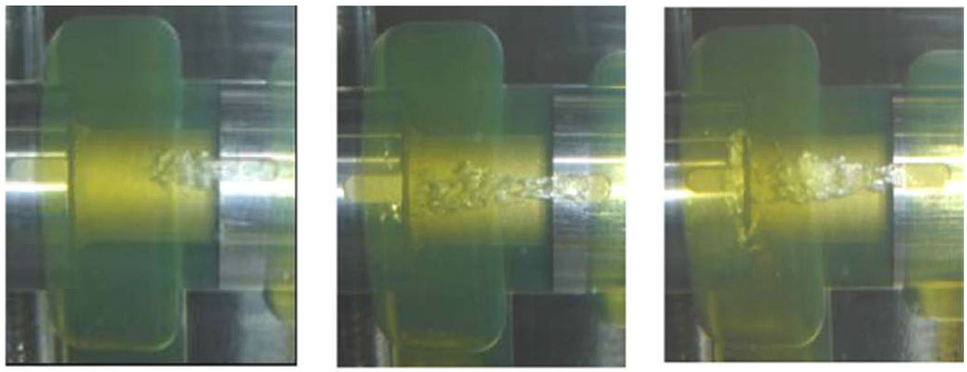
Fig. 15 Cavitation under different inlet velocities in pilot control globe valves [78]

[95, 96] used characteristic diagrams which were the relationship between the square root of pressure difference and the flow rate and acoustic waveform analysis to predict whether the globe valve underwent cavitation. It was found that when the opening percentage is lower than 12%, the variation in high-frequency signal could be analyzed to predict cavitation situations with lower energy, but under higher opening percentage, the acoustic signals could not be measured. Kudźma and Stosiak [97] found that in lift valves, the acoustic pressure level had an apparent increase and the occurrence of cavitation could be determined with the acoustic signal. Lu et al. [98] found in spool valves the peak acoustic frequency caused by bubble collapse decreased with the decrease in the cavitation number, and the cavitation acoustic spectral distri-



(a) opening: 1 mm, flow rate: 15 m^3/h **(b)** opening: 16 mm, flow rate: 48 m^3/h

Fig. 16 Cavitation in globe valves [89]



(a) x=1mm **(b)** x=2mm **(c)** x=3mm

Fig. 17 Cavitation increases with the increasing valve opening [82]

Table 4 Literature on the parameters that affected by cavitation

References	Valve type	Working fluid	Methods	Turbulence model
Caillaud et al. [91]	Globe-style valve	Water	Experiments	–
Ferrari and Leutwyler [89]	Globe valve	Water	Experiments + CFX	RNG k–ε/SST k–ω
Shirazi et al. [87]	Ball valve	Water	CFD	Standard k–ε
Pinho et al. [85]	Safety relief valves	Water	Experiments	–
Amirante et al. [86]	4/3 proportional directional valve	Liquid oil	Experiments + Schnerr–Sauer model	RNG k–ε
Tabrizi et al. [88]	Ball valve	Water	CFD	SST k–ω
Yi et al. [90]	Conical relief valve	Oil	Experiments	–
Okita et al. [92]	Hydraulic relief valve	Oil	Experiments + modified cavitation mode [83] based on Chen and Heister model [84]	Not described

butions had good coherence with the Strouhal number. The power spectrum density of dynamic pressure inside throttle valves could be used as a criterion to illustrate the cavitation intensity [107].

Ai-Fang and Yang [99] proposed a new maximum stress judgment criterion shown as follows:

$$P = -\frac{1}{3}\text{Trace } T = -\frac{1}{3}(T_{11} + T_{22} + T_{33}) \quad (3)$$

$$S = 2\mu D[u] = \begin{bmatrix} S_{11} & S_{12} & 0 \\ 0 & S_{22} & S_{23} \\ 0 & 0 & S_{33} \end{bmatrix} \quad (4)$$

where p is the average positive stress, $D[u]$ is symmetric part of velocity gradient, μ is viscosity. When $P - \max(S_{ij}) < p_c$, cavitation will be generated. They found that the model proposed by Singhal et al. together with the maximum stress judgment criterion could effectively predict the primary cavitation in V-type valve port.

Methods to minimize cavitation

Many methods have been suggested by lots of researchers, for example, improving the shape of cross section, adding a pressure reducing device, or optimizing the valve geometrical structure. The literature focusing on the methods to minimize cavitation in control valves is shown in Table 5.

The square shape of flapper can reduce cavitation relatively, and the rectangular shape can minimize or suppress cavitation significantly compared with the traditional shape of flapper (Fig. 18) in electrohydraulic servo-valves [101] and flapper–nozzle pilot valves [102]. Liu et al. [103] found that a two-step throttle had lower cavitation inception possibility compared with a single-step throttle in water hydraulic valves, which was also found in throttle valves [51], and the two-step throttle with sharp edge had better anti-cavitation ability than the one with chamfer edge.

Adding a cage inside globe valves can make cavitation primarily appear in regions close to itself, and the valve body can be protected (Fig. 19) [104]. An orifice plate is suggested to be placed behind the valve to minimize cavitation [105], and fins are suggested to attach to the valve body of butterfly valves to reduce the cavitation noise adequately [106]. Weijie et al. [107] installed a drainage device in the valve body of throttle valves to suppress cavitation, and they found that the cavitation suppression capacity of the drainage device increased firstly and then decreased. The effect of cavitation suppression decreased with the increasing outlet pressure. Wilson and Boelen [108] also proposed that anti-cavitation trim should be installed or a small startup valve should be combined with a large main valve to prevent cavitation in a feed water valve.

Ogawa and Hisada [109] found that in butterfly valves, while the ditch depth was equal to one-fifth of the duct height and the ditch length was equal to the duct height, the reduction in cavitation noise had the greatest value, and the secondary cavitation noise could also be eliminated by varying the ditch shape. Feng et al. [110] found that in a tainter valve, the top slop at the outlet should be reduced and the horizontal length should be shortened when the lateral offsets width was small to eliminate cavitation. Kim et al. [111] found that by changing the spring constants of delivery valves, the flow area, and spring constants of constant pressure valves, the cavitation could be prevented. Xu and Xuan [112] found that in a ship lock valve, cavitation possibility could be reduced by a sudden culvert expansion behind valves, and the gap cavitation could be eliminated and the valve lip cavitation could be eased by the top seal gap aeration. Trivedi et al. [113] found the aged gate valve had a lower likelihood of cavitation compared with non-aged gate valves.

Table 5 Literature focusing on the methods to minimize cavitation in control valves

References	Valve type	Working fluid	Methods	Turbulence model
Xu and Xuan [112]	Ship lock Valve	Water	Experiments	–
Feng et al. [110]	Tainter valve stand	Water	Experiments + CFD	Not described
Liu et al. [103]	Two-step throttle	Tap water	Experiments	–
Ogawa and Hisada [109]	Butterfly valve	Water	Experiments + CFD2000 (cavitation not considered in simulation)	Not described
Kim et al. [111]	Delivery valve and constant pressure valve in a fuel injection system	Diesel	FLUENT	Not described
Ogawa [106]	Butterfly valves	Water	Experiments	–
Chern et al. [104]	Globe valve	Water	Cavitation model described by Hympendahl [100]	Standard k–ε
Trivedi et al. [113]	Gate valve	Water	CFD	k–ε
Aung and Li [101]	Electrohydraulic servo-valve	Hydraulic oils	Singhal et al. model	Standard k–ε
Yang et al. [102]	Flapper–nozzle pilot valve	Oil	Experiments + Singhal et al. model	Standard k–ε
Weijie et al. [107]	Hydraulic throttle valve	Water	Experiments	–

Fig. 18 Vapor fraction in two different shapes [101]

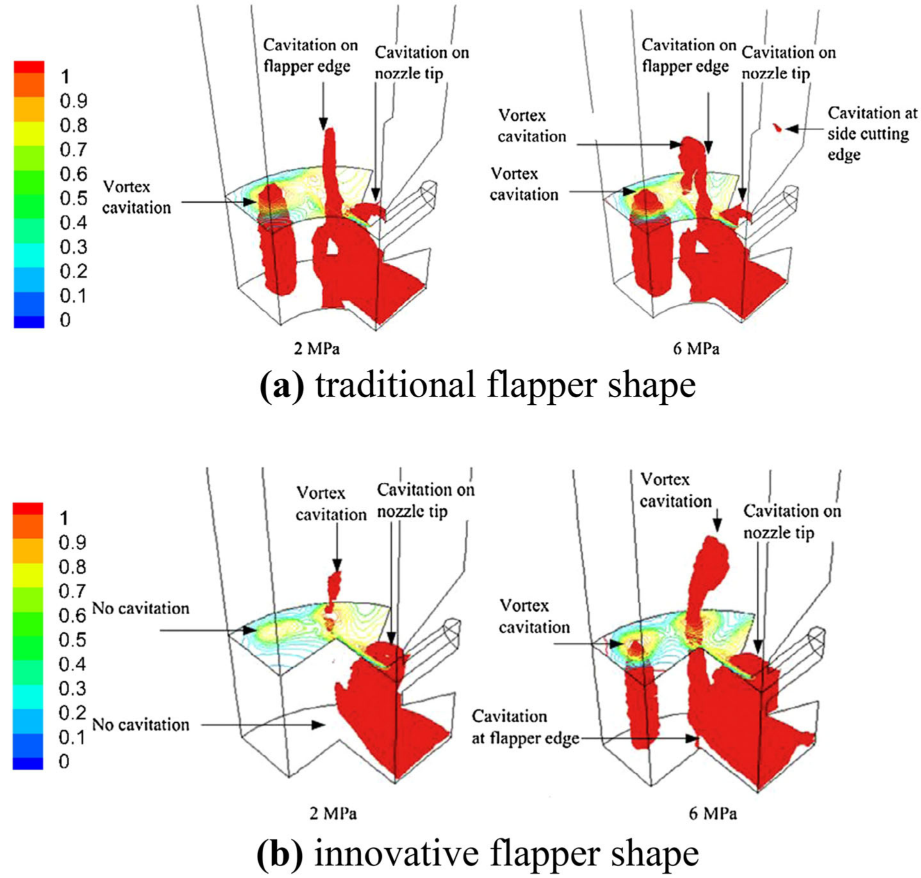
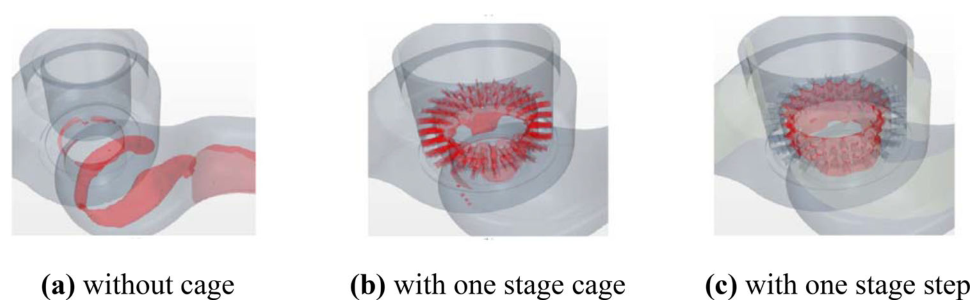


Fig. 19 Cavitation in fully open state at $t = 10$ s [104]



Future research

The works that have been done about cavitation in valves are valuable, but by reviewing the literature, it is believed that further improvement and trial are still needed.

For the numerical methods, although the cavitation models used by most researchers can be used to investigate cavitation inside valves, the model constants of cavitation models are not suitable for all conditions and need to be corrected. Moreover, when there is an intensive cavitating water jet, the compressibility of the cavitation bubbles better be considered [114, 115]; thus, new cavitation models need to be developed. Besides, the turbulence model used by most of the researchers is two-equation Reynolds-averaged Navier–Stokes equation (RANS) method, and it is proved that sometimes the LES model is more accurate [47] and the LES model has also been used in cavitating flow of other hydraulic machines [9]. For experimental methods, more visual experimental methods need to be applied to understand the flow fields inside control valves accurately, and ways of the real-time monitor of the cavitation inception in actual operation need to be explored.

Cavitation may occur during the open and close process of valves, and cavitation characteristics can be affected by the components movement like valve stem. Up to now, most works are related to the fixed opening of valves and more works need to be carried out concerning the open or close process.

When it comes to the analysis of the closing dynamics of mechanical heart valves, lots of numerical simulation work can be found using fluid–structure interaction (FSI) method [116–118], but the analysis about cavitation in mechanical heart valves is all experiments as we can find. With the rapid development and improvement in numerical simulation, numerical methods need to be done to help understand the internal cavitation characteristics.

Conclusion

The current work basically presents recent research works on cavitation in valves including mechanical heart valves and control valves. With the technical progress in the computational calculation and experimental measurements, the complex flow inside various valves can be observed, solved, and understood. This study is mainly divided into two categories, and the following conclusions based on our review can be got.

1. Two kinds of prosthetic valves including monoleaflet and bileaflet mechanical heart valves are discussed and summarized, and mechanical heart valves may undergo damage due to the cavitation occurring at the instant of valve closure. The main cause of cavitation inside MMHVs and BMHVs is the squeeze flow and water hammer phenomenon. The location where cavitation may occur, the last time of the occurrence of cavitation, the effects of structural parameters on cavitation intensity, the measurement and analysis methods of cavitation inside prosthetic valves were discussed based on the past published literature. Moreover, the comparison of the cavitation intensity between two kinds of prosthetic valves is concluded.
2. The common method to investigate cavitation in control valves is computational fluid dynamics, and the commonly applied cavitation models are the Singhal et al. model, Schnerr–Sauer model, and Zwart–Gerber—Belamri model. Cavitation in various control valves is summarized into five parts: the occurrence and location of cavitation inside control valves, the parameters that affect the cavitation intensity, methods that are taken to minimize the intensity or inception of cavitation, the real-time assessment of the occurrence of cavitation and the measurement of cavitation, and the effects of the cavitation occurrence on other parameters like vibration and hydraulic force.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Human and animal rights This article does not contain any studies with human or animal subjects performed by any of the authors.

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