Asymmetric transmission of sound wave in cavitating liquids

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Two modes of the asymmetric sound transmission are observed experimentally in a one-dimensional system composed of coupled two layers of liquids. Their cavitation thresholds are different from each other. When the sound wave propagates from the high-threshold liquid to the low-threshold liquid, the two liquids can avoid the cavitation for a medium driving pressure. When it propagates from the low-threshold liquid to the high-threshold liquid, however, the low-threshold liquid can be cavitated by the same driving pressure, though the high-threshold liquid remains uncavitated. Therefore, there is a sound transmission asymmetry, or sound rectification in this double-layer liquid. Furthermore, when the system is driven by a high pressure, cavitation can take place in both high- and low-threshold liquids in the sound transmission from the high-threshold liquid to the low-threshold liquid, but only the low-threshold liquid can be cavitated in the opposite transmission. This mechanism gives an asymmetry with reversed rectifying direction. The efficiency of rectification is related to the driving sound pressure and the cavitation thresholds of the two liquids based on experimental results. Finally, the experimental observations are reproduced by the numerical simulation based on the modified two-phase fluid mechanics.

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I. INTRODUCTION

The electron diode, invented by Fleming more than 100 years ago, is widely applied in modern circuit to revolutionize our life dramatically. Besides, it is the first component of realizing one-direction transmission of energy. It encourages researchers to investigate the asymmetric transmission of other kinds of energy. Recently, with the development of numerical calculation, researchers have made significant progress in this field. Li *et al.* numerically simulated the coupled Frenkel-Kontorova lattice model and found that its microphenomenon deviates from the Fourier thermal conductivity law. The asymmetric energy transmission phenomenon, which is referred to as heat rectification was reported [1]. After that, investigation using equivalent LC transmission circuit supports the phenomenon of heat rectification as well [2]. The asymmetric transmission of acoustic energy, namely the acoustic diode, was also proposed and verified by experiments during the same period [3,4]. All of the asymmetric transmission systems mentioned above are usually carefully designed. During our research on the propagation of sound wave in cavitating liquids, we found the asymmetric transmission also exists in a simple double-layer liquid system when the powerful ultrasound transmits through it. Furthermore, the direction of sound energy rectification can be reversed under different driving sound pressures.

II. MODEL AND MECHANISM

We consider a simple harmonic sound wave propagating from one end with driving sound pressure amplitude P_{dr} to the other end with output sound pressure amplitude p_{out} in a one-dimensional two layers of liquids coupled by a sound passing membrane. The thickness of each layer is a. The distributions of sound pressure amplitude are qualitatively plotted in Fig. 1. For the transmission from the left liquid to the right one (L-R transmission), $P_{dr} = P_L$ and $p_{out} = p_R$. Otherwise, $P_{dr} = P_R$ and $p_{out} = p_L$ for the R-L transmission. Let Q_L and Q_R to be the Blake cavitation threshold pressures [5,6] of the left and the right liquids, respectively, and $Q_L \geqslant Q_R$ without loss of generality. The asymmetry can exist between the L-R and R-L transmissions. If $Q_L > P_{dr} \geqslant Q_R$, it is possible that there is no cavitation in both left and right liquids for the L-R transmission. At first there should be no cavitation in the left liquid due to $P_{dr} < Q_L$. The sound pressure amplitude at the interface between two liquids, $p(0)$, has been decayed by the left liquid, so that $p(0) < P_{dr}$. If $p(0)$ is further lower than the threshold pressure of the right liquid Q_R, then the right liquid cannot be cavitated too. Therefore, there is no cavitation to be taken place for the L-R transmission. On the contrary, for the R-L transmission the right liquid will be cavitated because of $P_{dr} \geqslant Q_R$. As is well known, the cavitation will yield an additional attenuation called cavitation screening [7–9], leading to that the R-L transmission is more difficult than the L-R transmission. In other words, the sound wave is rectified in this system.

In order to quantitatively express the asymmetry of sound transmission, we define transmission coefficient $T = \frac{p_{out}}{P_{dr}}$, then the right transmission coefficient $T_R = p_R/P_L$ and the left transmission coefficient $T_L = p_L/P_R$ for the L-R and R-L transmissions, respectively. Moreover, we introduce a dimensionless coefficient,

$$\chi \equiv 2\frac{T_R - T_L}{T_R + T_L} = 2\frac{p_R - p_L}{p_R + p_L}, \quad (1)$$

to illustrate the asymmetry of sound transmission. $p_R > p_L$, which means the sound propagates more easily in the L-R transmission than in the R-L transmission, leads to

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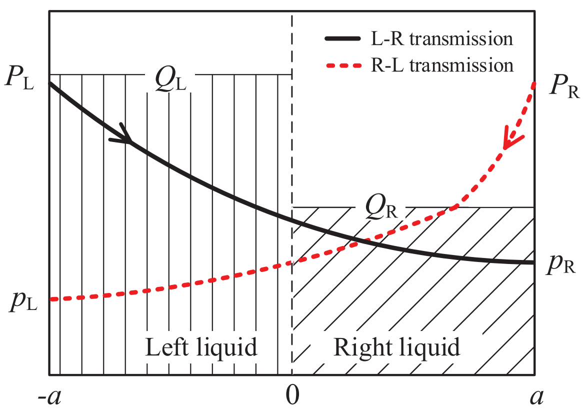

FIG. 1. Schematic diagram of the system. The solid and dash lines represent the sound pressure amplitude of L-R transmission and R-L transmission, respectively.

$\chi > 0$, otherwise $\chi < 0$. Of course, $\chi = 0$ corresponds to the symmetric transmission of sound wave.

III. ASYMMETRIC SOUND TRANSMISSION SYSTEM

For verifying the mechanism of asymmetric transmission, we design the experimental system as shown in Fig. 2. The cross section of the rectangle glass container is 0.09×0.09 m^2 and the length of each layer of the host liquids a is 0.1 m. Both end faces of the container are stainless steel plates of 0.5 mm in thickness, and two ultrasound transducers (40 kHz) are bonded to the outer sides of two end faces. A polyethylene waterproof sound passing membrane with 0.1 mm in thickness is fixed at the middle of the container to separate the left and right liquids. In our experiment, the host liquids are 28 vol% alcohol solution [AS(28%)], AS(20%), and water, and their cavitation threshold pressures are 0.4, 0.5, and 0.9 bar, respectively. Acoustic absorbing material is attached to the internal lateral face of the container to eliminate the reflection of sound wave as much as possible [10]. During experiment the liquids are cycled continuously so that the properties of the host liquids keep unchanged. The temperature of liquids is maintained at 20 ± 2°C.

A sinusoidal signal at 40 kHz is output from a function generator (Agilent 28335A, U.S.), then amplified by a power amplifier (B&K 2716, Denmark) to drives the transducer L or R after impedance matching. The L-R transmission with $P_{dr} = P_L$ and $p_{out} = p_R$ or the R-L transmission with $P_{dr} = P_R$ and $p_{out} = p_L$ is chosen by a switch. A programed scanning system is constructed for quickly and precisely measuring the sound field in the container. There are two orthogonal guide rails parallel and perpendicular to the container in the system, respectively. Two slide blocks are rode on them, respectively (Fig. 2). A needle hydrophone (RESON TC4013, Denmark) is held at the vertical slide block to measure the sound pressure in the container. Both the two blocks can move under the control of step-motors at the minimum spatial resolution of 0.05 mm. The output of the hydrophone is fed to a digital oscilloscope (Agilent Infiniium 54810, U.S.). Sampling rate of the oscilloscope is set to be 2.4 MHz and the duration of each recording is 1 ms, 40 cycles of the driving sound wave. The function generator, motor-control circuit, and oscilloscope are programmably controlled by a main computer through its GPIB and serial port. The amplitude of fundamental sound pressure is obtained by extracting the fundamental component from the time-domain data acquired by the oscilloscope after FFT and calibration. The measuring step of the horizontal block is 5 mm. Every amplitude data is binned over itself and its left and right adjacent measurements to smooth the spatial jumping due to cavitation. The distributions of cavitation bubbles are captured by a long-distance microscope (Hirox KH3000V, Japan) with frame rate 5000 fps (not shown).

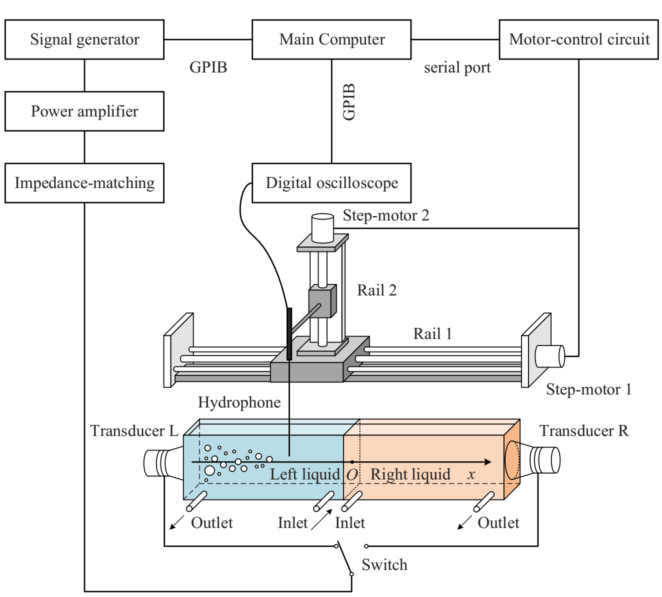

FIG. 2. Schematic diagram of the experimental system.

IV. EXPERIMENTAL OBSERVATIONS

In our experiment the right liquid is AS(28%) whose threshold pressure is the lowest among the host liquids, that is, $Q_R = 0.4$ bar, while the left liquid can be chosen from the other host liquids.

At the beginning, the water with the threshold pressure $Q_L = 0.9$ bar is chosen as the left liquid, and P_{dr} is set to be 0.6 bar, so $Q_L > P_{dr} > Q_R$, the same case as mentioned in Sec. II. Figure 3 shows the distributions of sound pressure amplitude $p(x)$ in this system, which consist with our prediction in Sec. II (see Fig. 1). Indeed, hardly any cavitation bubbles have been observed in both two liquids in the L-R transmission [see inset (a) in Fig. 3]. Nevertheless, in the R-L transmission some bubbles are clearly visible in the right liquid [see inset (b) in Fig. 3)]. As a result, the L-R and R-L transmissions of sound wave show asymmetric, that is, $p_R > p_L$ and $\chi > 0$.

Then, we set $P_{dr} = 1.8$ bar, so $P_{dr} > Q_L > Q_R$. The distributions of $p(x)$ are plotted in Fig. 4, where the asymmetry between the L-R and R-L transmissions is still observed. $p(x)$ almost maintains higher than Q_L and Q_R in the L-R transmission, whereas it only remains higher than Q_R in the right liquid in the R-L transmission. Furthermore, $p_R < p_L$ and $\chi < 0$. It is a mechanism of the asymmetric transmission that differs from that described above or in Sec. II. We believe

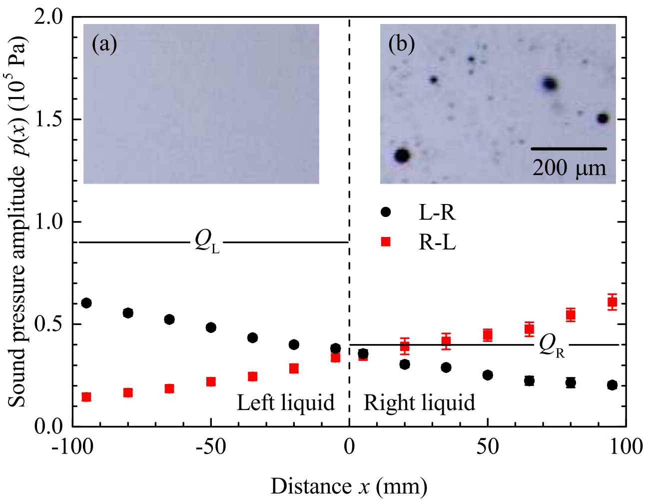

FIG. 3. Distributions of sound pressure amplitude in water-AS(28%) system driven by $P_{dr} = 0.6$ bar. The insets (a) and (b) are the distributions of cavitation bubbles (black regions) captured at 30 mm to transducer L of L-R transmission and transducer R of R-L transmission, respectively.

larger scope of cavitation results in greater attenuation, leading to $\chi < 0$. In order to distinguish these two mechanisms, we call the asymmetric transmission with $\chi > 0$ in Sec. II as Mode 1, and $\chi < 0$ as Mode 2, respectively. These experiments show the direction of rectification, namely the polar of χ, is dependent on P_{dr} with respect to the cavitation threshold pressures of the host liquids.

Finally, we note that the system will lose the asymmetry if the gap between Q_L and Q_R vanishes. Therefore, it is easy to guess the efficiency of the rectification, namely the magnitude of χ, is also related to the gap. To verify it, we set the left liquid to be AS(20%) whose cavitation threshold is 0.5 bar, near to that of the right liquid, and $P_{dr} = 1.8$ bar. The observations of $p(x)$ in the L-R and R-L transmissions show that the output sound pressures p_R and p_L are approximately

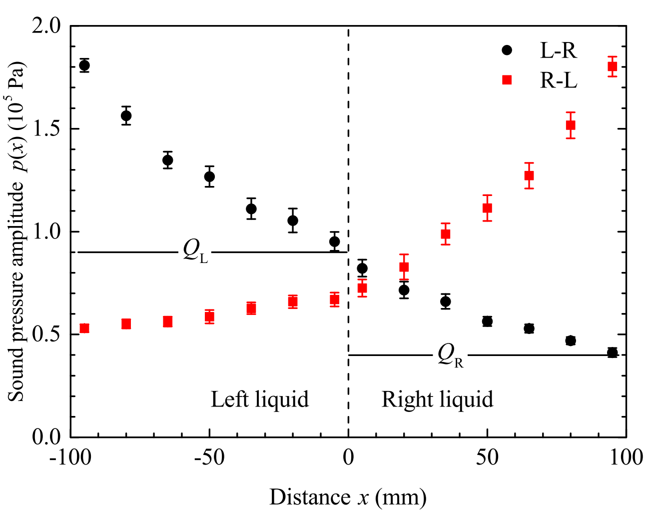

FIG. 4. Distributions of sound pressure amplitude in water-AS(28%) system driven by $P_{dr} = 1.8$ bar.

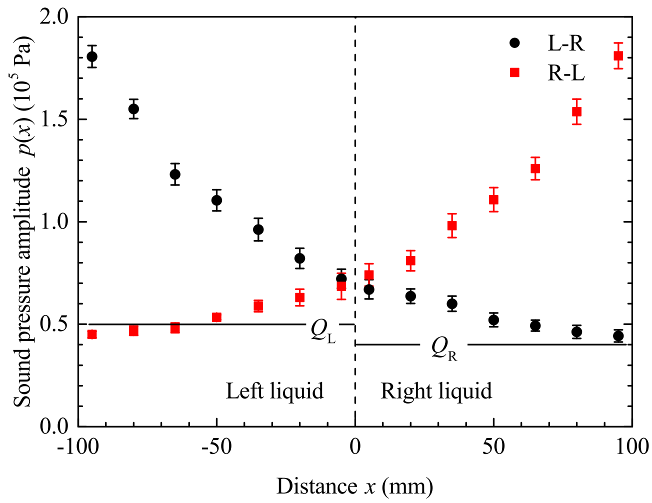

FIG. 5. Distributions of sound pressure amplitude in AS(20%)-AS(28%) system driven by $P_{dr} = 1.8$ bar.

equal, leading to $\chi \approx 0$ (see Fig. 5). We can conclude that a large threshold gap is necessary for realizing the remarkable asymmetric transmission of sound wave.

V. THEORY AND SIMULATION

The sound wave propagating in cavitating liquid can be described by the Helmholtz equation [11,12],

$$\nabla^2 p + k_m^2 p = 0, \tag{2}$$

where p is the sound pressure amplitude and k_m is the complex wave number expressed as

$$k_m = \frac{\omega}{c_m} - i\alpha_\eta, \tag{3}$$

with ω and c_m being the angular frequency and the velocity of sound wave in cavitating liquid, respectively. α_η includes the attenuation and the energy transferring to harmonics. Both c_m and α_η are tedious functions of the volume fraction $\beta(x)$ of the two-phase liquid [11,12]. For our experimental condition, we assume $\beta(x)$ is positively related to the local sound pressure $p(x)$ exceeding the cavitation threshold $Q(x)$, that is,

$$\beta(x) = \begin{cases} 0 & p(x) < Q(x) \\ B[p(x) - Q(x)] & p(x) \geqslant Q(x) \end{cases}, \tag{4}$$

where B is a model parameter.

In the theoretical model of Ref. [12], the authors only take account of the attenuation caused by cavitation bubbles. In our situation the bulk attenuation of the host liquids is not ignorable, so that an additional attenuation coefficient α_0 has been inserted into α_η [13], that is, $\alpha_0 + \alpha_\eta \to \alpha_\eta$.

By solving Eq. (2) the sound pressure amplitude distribution can be acquired. For our double-layer liquid, water-AS(28%), the cavitation threshold function $Q(x)$ can be expressed as

$$Q(x) = \begin{cases} Q_L & -a \leqslant x \leqslant 0 \\ Q_R & 0 < x \leqslant a \end{cases}, \tag{5}$$

where $a = 0.1$ m, $Q_L = 0.9$ bar, and $Q_R = 0.4$ bar, respectively. The bulk attenuation coefficient α_0 and angular

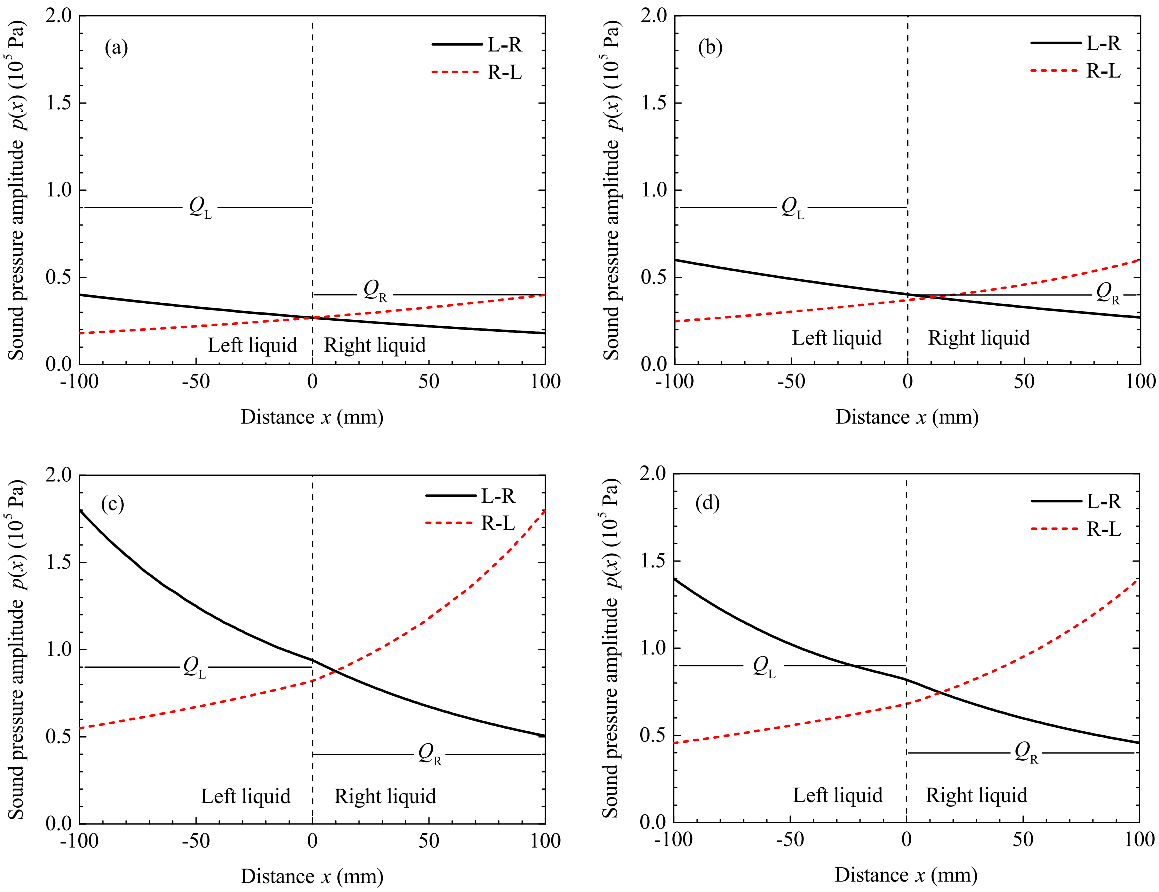

FIG. 6. Calculated distributions of the sound pressure amplitude in water-AS(28%) system driven by (a) $P_{dr} = 0.4$ bar, (b) $P_{dr} = 0.6$ bar, (c) $P_{dr} = 1.8$ bar, and (d) $P_{dr} = 1.4$ bar, respectively.

frequency ω are set to be 4.0 m^{-1} and $2\pi \times 40$ kHz, respectively, and $B = 2.0\times10^{-8}$ Pa^{-1}, the other parameters used in numerical simulation are the same as those in Ref. [12].

Figure 6 shows the calculated distributions of the sound pressure amplitude in the water-AS(28%) driven by 0.4, 0.6, 1.8, and 1.4 bar, respectively. It is obvious that there is no any asymmetric transmission to be appeared in the double-layer liquid if the driving sound pressure amplitude is lower than both threshold pressures Q_L and Q_R [see Fig. 6(a)]. When P_{dr} rises, $P_{dr} = 0.6$ bar for example, the distribution of the sound pressure [Fig. 6(b)] shows that the system undergoes the asymmetric transmission of Mode 1 (see Fig. 3). If $P_{dr} =$ 1.8 bar, the distribution [Fig. 6(c)] reproduces the experimental asymmetric transmission of Mode 2 (Fig. 4). It is interesting that if the driving sound pressure is between 0.6 and 1.8 bar, such as 1.4 bar, the distributions show the competition between these two modes. As a result, $P_R \approx P_L$, and the transmissions recover to symmetric [see Fig. 6(d)].

For further exploring the effect of Q_L and Q_R on χ, we fix P_{dr} at 1.0 bar, meanwhile change Q_L and Q_R from 0.1 to 1.0 bar, keeping $Q_L \geqslant Q_R$. The outcome of simulation plotted in Fig. 7 shows that the variation of χ to Q_L and Q_R is complicated: (1) If Q_R is fixed, for example, at 0.1 bar, χ will decrease to be negative and then rise to be positive with Q_L, which means the asymmetric transmission changes from Mode 2 to Mode 1 during this procedure. (2) If Q_L is fixed at 1.0 bar, χ increases and then falls down with the increasing of Q_R. The asymmetric transmission maintains at Mode 1 due to $\chi > 0$. (3) When $Q_L = Q_R$, $\chi = 0$, the asymmetry vanishes.

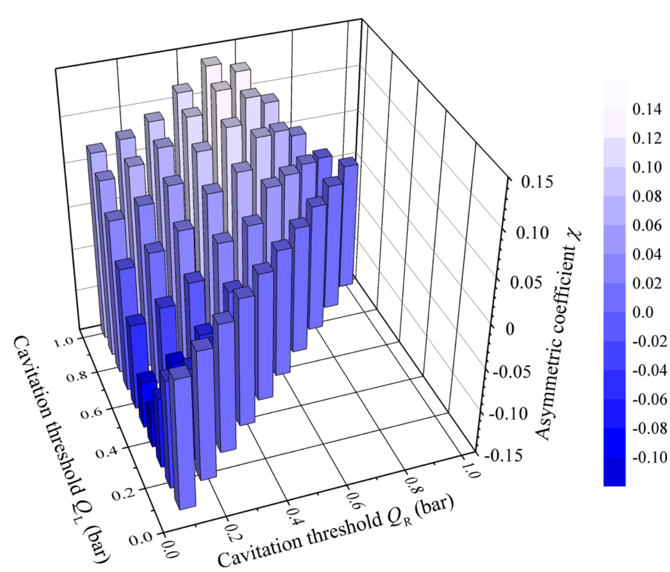

FIG. 7. Calculated asymmetric coefficient as a function of the cavitation thresholds of the left and right liquids.

VI. CONCLUSION AND DISCUSSION

The asymmetric transmission of sound wave is experimentally observed in the double-layer liquid system. When the driving sound pressure amplitude is a proper value between the cavitation threshold pressures of the two liquids, cavitation does not happen when the sound wave propagates from the high threshold liquid to the low one, whereas part of the low threshold liquid will be cavitated when it propagates oppositely. The sound pressure is asymmetrically distributed and the output pressure of the opposite direction is low. Another rectification mode is found when the driving sound pressure amplitude becomes higher than the cavitation thresholds of both liquids. Both liquids will be cavitated when the sound wave propagates from the high-threshold liquid to the low-threshold liquid, but only the low-threshold liquid will be cavitated when the sound wave propagates in the opposite direction, so the output sound pressure of the opposite direction is high. Competition exists between these two modes when the driving pressure is a medium value, and the asymmetry may disappear under some circumstances. That means the rectification direction and effect of our system are strongly dependent on the driving sound pressure and the cavitation thresholds of the host liquids, which is different from the model proposed before in mechanism [3,14–17]. Numerical simulation conforms with the experimental results qualitatively and illustrates more details. It is necessary to improve the rectification effect of the system by adjusting the parameters in our later work.

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