United States Patent	12392751
Kind Code	B2
Date of Patent	August 19, 2025
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Fluid device

Abstract

A fluid device includes a flow path through which a fluid flows, and an ultrasonic element that transmits an ultrasonic wave to the fluid to generate a standing wave in the fluid in the flow path along a first direction orthogonal to a flowing direction of the fluid. The ultrasonic element includes a vibrator having a fluid contact surface that comes into contact with the fluid, and a piezoelectric element that is provided at the vibrator and that flexurally vibrates the vibrator in a normal direction of the fluid contact surface. When a thickness of the vibrator in the normal direction is t, a sound velocity of a medium of the fluid is C, an average sound velocity of a longitudinal wave transmitted in the vibrator is C′, a dimension of the flow path in the first direction is L, and a mode order of the standing wave is n, the following expression is satisfied. $t < \frac{C'}{C} \times \frac{L}{2n}$

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Appl. No.: **17/388585**

Filed: **July 29, 2021**

Prior Publication Data

Document Identifier	Publication Date
US 20220034846 A1	Feb. 03, 2022

Foreign Application Priority Data

JP	2020-129407	Jul. 30, 2020

Publication Classification

Int. Cl.: G01N29/032 (20060101); **B01L3/00** (20060101); **G01N29/22** (20060101); **G01P5/24** (20060101)

U.S. Cl.:

CPC **G01N29/032** (20130101); **B01L3/502761** (20130101); **G01N29/221** (20130101); **G01N29/222** (20130101); B01L2400/0439 (20130101); G01N2291/011 (20130101); G01P5/241 (20130101)

Field of Classification Search

CPC: B01L (2400/0439); G01N (29/032); G01N (29/221); G01N (29/222); G01N (2291/011); G01P (5/241)

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Background/Summary

(1) The present application is based on, and claims priority from JP Application Serial Number 2020-129407, filed Jul. 30, 2020, the disclosure of which is hereby incorporated by reference herein in its entirety.
BACKGROUND
1. Technical Field
(2) The present disclosure relates to a fluid device.

2. Related Art

(3) In related art, a fluid device that performs acoustic convergence on fine particles in a fluid is known.

(4) For example, a fluid device disclosed in "Enhancement in acoustic focusing of micro and nanoparticles by thinning a microfluidic device", Nobutoshi Ota, 6 others, December 2019, Royal Society Open Science, Volume 6, Issue 2, Article No. 181776 includes a flow path substrate such as a glass substrate in which a flow path is formed, and a piezoelectric element provided at the flow path substrate. An ultrasonic wave generated by the piezoelectric element is transmitted to an inside of the flow path via the flow path substrate, and generates a standing wave in a fluid in the flow path. Fine particles in the fluid converge in a predetermined range in the flow path due to a pressure gradient formed by the standing wave.

(5) However, in the fluid device disclosed in "Enhancement in acoustic focusing of micro and nanoparticles by thinning a microfluidic device", since a difference between an acoustic impedance of the fluid and an acoustic impedance of the flow path substrate is large, when the ultrasonic wave generated by the piezoelectric element is propagated from the flow path substrate to the fluid, most of the ultrasonic waves are reflected at a boundary between the flow path substrate and the fluid. Therefore, transmission efficiency of the ultrasonic wave to the fluid is lowered, and as a result, a drive voltage and a driving frequency that are applied to the piezoelectric element for generating the standing wave increase.

SUMMARY

(6) A fluid device according to an aspect of the present disclosure includes: a flow path through which a fluid flows; and an ultrasonic element configured to transmit an ultrasonic wave to the fluid to generate a standing wave in the fluid in the flow path along a first direction orthogonal to a flowing direction of the fluid. The ultrasonic element includes a vibrator having a fluid contact surface that comes into contact with the fluid, and a piezoelectric element that is provided at the vibrator and that is configured to generate flexural vibration to the vibrator in a normal direction of the fluid contact surface. When a thickness of the vibrator in the normal direction is t, a sound velocity of a medium of the fluid is C, an average sound velocity of a longitudinal wave transmitted in the vibrator is C', a dimension of the flow path in the first direction is L, and a mode order of the standing wave is n, the following expression is satisfied.

(7) $t < \frac{C'}{C} \times \frac{L}{2n}$

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. **1** is a cross-sectional view schematically showing a part of a fluid device according to a first embodiment.

(2) FIG. **2** is a cross-sectional view taken along a line A-A in FIG. **1**.

(3) FIG. **3** is a cross-sectional view schematically showing a part of a fluid device according to a second embodiment.

(4) FIG. **4** is a cross-sectional view taken along a line B-B in FIG. **3**.

(5) FIG. **5** is a cross-sectional view schematically showing a part of a fluid device according to a third embodiment.

(6) FIG. **6** is a cross-sectional view taken along a line C-C in FIG. **5**.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

First Embodiment

(7) Hereinafter, a fluid device **10** according to a first embodiment will be described with reference to FIGS. **1** and **2**.

(8) FIG. **1** is a cross-sectional view schematically showing a part of the fluid device **10** according

to the first embodiment, and FIG. **2** is a cross-sectional view taken along a line A-A in FIG. **1**.

(9) The fluid device **10** includes a flow path substrate **30** in which a flow path **20** is formed, and an ultrasonic wave generation unit **40** provided at the flow path substrate **30**.

(10) In the fluid device **10**, the ultrasonic wave generation unit **40** applies ultrasonic waves to a fluid S flowing through the flow path **20**, thereby generating a standing wave SW with any mode order along one direction orthogonal to a flowing direction of the fluid S. In a process of fine particles M dispersed in the fluid S flowing through the flow path **20**, the fine particles M are affected by a pressure gradient formed by the standing wave SW, and are converged in a predetermined range in the flow path **20**.

(11) In such a fluid device **10**, for example, a concentration of the fine particles Min the fluid S can be increased by providing, in the flow path **20**, a concentration flow path through which the fluid S in the predetermined range selectively flows and a discharge flow path through which the fluid S in a range other than the predetermined range selectively flows. In the predetermined range, the fine particles M are converged.

(12) In FIG. **1**, a state of the fine particles M converged by the standing wave SW of a first-order mode is schematically illustrated. In FIG. **2**, illustration of the fine particles M is omitted, and the standing wave SW generated in the flow path **20** is shown as a pressure waveform.

(13) Configuration of Fluid Device **10**

(14) A schematic configuration of the fluid device **10** will be described with reference to FIG. **2**.

(15) The flow path substrate **30** is a substrate in which the flow path **20** is formed. The flow path substrate **30** can be formed, for example, by joining a pair of substrates having groove portions corresponding to the flow path **20** to each other. The substrates constituting the flow path substrate **30** are not particularly limited, and for example, a glass substrate or a silicon substrate can be used.

(16) Although not shown, the flow path substrate **30** is formed with an injection port for injecting the fluid S into the flow path **20** and one or more discharge ports for discharging the fluid S from the flow path **20**. When the flow path **20** is coupled to each of the concentration flow path and the discharge flow path as described above, each of these flow paths is formed with the discharge port.

(17) In the present embodiment, a cross section of the flow path **20** formed in the flow path substrate **30** is rectangular, and a depth direction of the flow path **20** coincides with a thickness direction of the flow path substrate **30**. The flowing direction of the fluid S flowing through the flow path **20** is orthogonal to the depth direction of the flow path **20**, and a width direction of the flow path **20** is orthogonal to each of the depth direction of the flow path **20** and the flowing direction of the fluid S.

(18) Hereinafter, the flowing direction of the fluid S is referred to as an X direction, the width direction of the flow path **20** is referred to as a Y direction, and the depth direction of the flow path **20** is referred to as a Z direction. The X, Y, Z directions are orthogonal to one another.

(19) The flow path substrate **30** includes an upper wall portion **31** constituting a wall portion of the flow path **20** on one side in the Z direction, a lower wall portion **32** constituting a wall portion of the flow path **20** on the other side in the Z direction, and side wall portions **33**, **34** constituting wall portions of the flow path **20** on both sides in the Y direction.

(20) The flow path substrate **30** is formed with a through hole **311** penetrating the upper wall portion **31** in the Z direction.

(21) The ultrasonic wave generation unit **40** is provided at the flow path substrate **30** so as to close the through hole **311** of the flow path substrate **30**. Accordingly, the ultrasonic wave generation unit **40** forms a part of the wall portion of the flow path **20**.

(22) Specifically, the ultrasonic wave generation unit **40** includes an element substrate **41**, a vibration film **42** supported by the element substrate **41**, and a piezoelectric element **43** provided at the vibration film **42**.

(23) The element substrate **41** is a semiconductor substrate made of Si or the like. The element substrate **41** is disposed in the through hole **311** of the flow path substrate **30** such that a thickness

direction of the element substrate **41** is along the Z direction, and an outer peripheral surface of the element substrate **41** is in liquid-tight contact with an inner peripheral surface of the through hole **311** of the flow path substrate **30**.

(24) The element substrate **41** is formed with an opening portion **411** penetrating the element substrate **41** along the thickness direction of the element substrate **41**.

(25) The vibration film **42** is formed of a laminated body or the like, in which a plurality of types of films are laminated, such as a SiO.sub.2 film and a ZrO.sub.2 film. The vibration film **42** is supported by the element substrate **41**, and closes one side (an opposite side of the opening portion **411** from a flow path **20** side) of the opening portion **411**.

(26) A portion of the vibration film **42** that overlaps the opening portion **411** when viewed from the thickness direction of the element substrate **41** constitutes a vibrator **421** that transmits ultrasonic waves. One surface of a pair of surfaces of the vibrator **421** serves as a fluid contact surface **422** that is to be in contact with the fluid S flowing into the opening portion **411** from the flow path **20**.

(27) Here, the vibration film **42** is disposed such that the thickness direction (a normal direction of the fluid contact surface **422**) of the vibration film **42** is along the Z direction.

(28) The piezoelectric element **43** is provided at an opposite-side surface of the vibrator **421** from the fluid contact surface **422**. Although not shown, the piezoelectric element **43** is formed by sequentially laminating a lower electrode, a piezoelectric film, and an upper electrode on the vibrator **421**.

(29) In such an ultrasonic wave generation unit **40**, an ultrasonic element **44** includes the vibrator **421** and the piezoelectric element **43** disposed on the vibrator **421**.

(30) In the ultrasonic element **44**, the piezoelectric element **43** is coupled to a drive unit (not shown). When a drive signal is input to the piezoelectric element **43** from the drive unit, a voltage is applied between the lower electrode and the upper electrode, and the piezoelectric film expands and contracts. Accordingly, the vibrator **421** flexurally vibrates in the normal direction of the fluid contact surface **422** at a predetermined oscillation frequency corresponding to a dimension W (an opening width of the opening portion **411**) of the vibrator **421** in a short-side direction or the like. The flexural vibration of the vibrator **421** is converted into a compressional wave of the fluid S to propagate the ultrasonic waves. The ultrasonic waves propagated to the fluid S are radially diffused around the vibrator **421**, and the ultrasonic waves traveling in the Y direction are repeatedly reflected by inner walls of the flow path **20**, thereby generating the standing waves SW in the flow path **20**.

(31) Here, in order to generate the standing wave SW in the Y direction in the flow path **20**, a flow path width L [m], which is a dimension of the flow path **20** in the Y direction, satisfies the following expression (1).

(32) $L = \frac{n \times C}{2F}$ (1)

(33) n is the mode order of the standing wave SW, C is a sound velocity [m/sec] of a medium of the fluid S, and F is a driving frequency [Hz] of the piezoelectric element **43**. The driving frequency F corresponds to the above-described oscillation frequency of the vibrator **421**.

(34) According to the above expression (1), it is assumed that when the sound velocity C of the medium is 1500 m/s when the medium is water, the mode order n of the standing wave SW is 1, and the driving frequency F of the piezoelectric element **43** is 600 kHz, the flow path width L is set to 1.25 mm.

(35) In order to prevent generation of a standing wave in the Z direction in the flow path **20**, a flow path depth H [m], which is a dimension of the flow path **20** in the Z direction, satisfies the following expression (2).

(36) $H < \frac{C}{2F}$ (2)

(37) According to the above expression (2), the flow path depth H is smaller than the flow path width L when the mode order n of the standing wave SW calculated by the above expression (1) is

1. That is, according to the above expressions (1), (2), the flow path **20** is formed such that the flow path depth H is smaller than the flow path width L.

(38) Alternatively, in order to prevent the generation of the standing wave in the Z direction in the flow path **20**, the flow path depth H may be set to be significantly larger than the flow path width L set by the above expression (1) without satisfying the above expression (2). In this case, a standing wave of a higher-order mode may be generated in the Z direction. However, such a standing wave of the higher-order mode has an acoustic power smaller than that of the standing wave SW generated in the Y direction, and thus an influence of the standing wave of the higher-order mode can be ignored.

(39) Thickness of Vibrator **421**

(40) When the piezoelectric element **43** is driven, not only a transverse wave that causes the flexural vibration of the vibrator **421**, but also a longitudinal wave that propagates inside the vibrator **421** is generated.

(41) When a thickness t of the vibrator **421** is larger than a wavelength λ of the longitudinal wave, the longitudinal wave becomes dominant in the vibrator **421**, and propagation efficiency of the ultrasonic wave from the vibrator **421** to the fluid S decreases. That is, this is equivalent to a state in which matching of acoustic impedances is not achieved.

(42) Even when the thickness t of the vibrator **421** is smaller than the wavelength λ of the longitudinal wave, the longitudinal wave is slightly generated in the vibration film **42**. In particular, when the thickness t of the vibrator **421** is equal to λ/4, the vibrator **421** functions as an acoustic matching layer of the longitudinal wave, and the longitudinal wave generated in the vibrator **421** is easily propagated to the fluid S. However, in a case of acoustic emission using the longitudinal wave, the propagation efficiency of the ultrasonic wave from the vibrator **421** to the fluid S is reduced as compared with a case of acoustic emission using the transverse wave.

(43) Therefore, in the present embodiment, the vibrator **421** is formed such that the thickness t is smaller than ¼ of the wavelength λ of the longitudinal wave. That is, the thickness t [m] of the vibrator **421** satisfies the following expression (3).

(44) $t < \frac{\lambda}{4}$ (3)

(45) The thickness t of the vibrator **421** is a dimension of the vibrator **421** along the normal direction with respect to the fluid contact surface **422**, and corresponds to a film thickness of the vibration film **42**.

(46) The wavelength λ [m] of the longitudinal wave in the above expression (3) is expressed by the following expression (4).

(47) $\lambda = \frac{C'}{F}$ (4)

(48) In the above expression (4), C′ is an average sound velocity [m/sec] of the longitudinal wave generated in the vibrator **421**, and F is the driving frequency [Hz] of the piezoelectric element **43**.

(49) According to the above expression (4), the above expression (3) is expressed by the following expression (5).

(50) $t < \frac{C'}{4F}$ (5)

(51) The driving frequency F in the above expression (5) satisfies the following expression (1) as described above.

(52) $L = \frac{n \times C}{2F}$ (1)

(53) In the above expression (1), L is the flow path width [m], n is the mode order of the standing wave SW, C is the sound velocity [m/s] of the medium of the fluid S, and F is the driving frequency [Hz] of the piezoelectric element **43**.

(54) According to the above expressions (1), (5), the thickness t of the vibrator **421** satisfies the following expression (6).

(55) $t < \frac{C'}{C} \times \frac{L}{2n}$ (6)

(56) The vibration film **42** according to the present embodiment is a laminated body of a plurality of films. That is, the vibrator **421** according to the present embodiment is constituted by a plurality of films. In this case, the average sound velocity C′ of the longitudinal wave generated in the vibrator **421** is calculated according to the following method.

(57) Here, when the number of films constituting the vibrator **421** is m, a thickness of each film constituting the vibrator **421** is t.sub.k (k=1, 2, . . . m), and an average of the longitudinal wave sound velocities in each film constituting the vibrator **421** is C.sub.k (k=1, 2, . . . m), the following expression (7) is established.

(58) $0 \ \frac{t}{C} \ = \ \text{.Math.}_{k=1}^{m} \ \frac{t_k}{C_k}$ (7)

(59) The thickness t of the vibrator **421** is expressed by the following expression (8).

$t = \Sigma.\text{sub.k}=1.\text{sup.m} t.\text{sub.k}$ (8)

(60) Therefore, according to the above expressions (7), (8), the average sound velocity C′ of the longitudinal wave generated in the vibrator **421** is expressed by the following expression (9).

(61) $C' \ = \ \dfrac{.\text{Math.}_{k=1}^{m} t_k}{.\text{Math.}_{k=1}^{m} \frac{t_k}{C_k}}$ (9)

(62) From a viewpoint of improving the propagation efficiency of the ultrasonic wave from the vibrator **421** to the fluid S, it is desirable that the thickness t of the vibrator **421** is a smaller value while satisfying the above expression (6).

(63) However, when the thickness t of the vibrator **421** becomes too small, a stress gradient in the thickness direction of the vibrator **421** becomes large, and thus, when the piezoelectric element **43** is driven, there is a high chance that the vibrator **421** is damaged.

(64) Therefore, in the present embodiment, as a result of an experiment in which the piezoelectric element **43** is driven by changing the dimension W of the vibrator **421** in the short-side direction and the thickness t of the vibrator **421**, it is preferable that the thickness t of the vibrator **421** satisfies the following expression (10).

(65) $8.03 \times 10^{-3} \times W \times E'^{-\frac{1}{3}} \times (\frac{n}{2} \times \frac{C}{L}) \leqq t$ (10)

(66) In the above expression (10), W is the dimension [m] of the vibrator **421** in the short-side direction, E′ is an average Young's modulus [Pa] of the vibrator **421** when a Poisson's ratio is 0.3, n is the mode order of the standing wave SW, and C is the sound velocity [m/sec] of the medium of the fluid S. When the thickness t of the vibrator **421** is smaller than a thickness obtained by a left side of the above expression (10), there is a high chance that the vibrator **421** is damaged.

(67) As described above, the vibrator **421** according to the present embodiment is constituted by a plurality of (m) films. In this case, the average Young's modulus E′ of the vibrator **421** can be expressed by the following expression (11).

(68) $E' \ = \ \frac{4}{d_m^m} \ .\text{Math.}_{i=1}^{i} \ E_i \{ (d_i -)^m - (d_{i-1} -)^m \}$ (11)

(69) α in the above expression (11) is defined by the following expression (12).

(70) $\ = \ .\text{Math.}_{i=1}^{m} \ \frac{E_i(d_i^2 - d_{i-1}^2)}{2E_i(d_i - d_{i-1})}$ (12)

(71) In the above expressions (11), (12), m is the number of films constituting the vibrator **421**, and E.sub.i (i=1, 2, . . . m) is the Young's modulus of each film constituting the vibrator **421** when the Poisson's ratio is 0.3.

(72) d.sub.i is expressed by the following expression (13).

$d.\text{sub.i} = \Sigma.\text{sub.k}=1.\text{sup.i} t.\text{sub.k}$ (13)

(73) In the above expression (13), t.sub.k (k=1, 2, . . . m) is the thickness of each film constituting the vibrator **421**. That is, d.sub.i is a value obtained by adding the thicknesses t.sub.k of the films constituting the vibrator **421** up to an i-th thickness.

(74) Here, when the fluid device **10** according to the present embodiment has the following configuration, it is preferable that the thickness t of the vibrator **421** falls within a range of the

following expression (14) using the expression (6) and the expression (10) described above.

(75) Dimension W of vibrator in short-side direction: 19 μm

(76) Flow path width L: 375 μm

(77) Sound velocity C of medium of fluid S: 1500 m/s

(78) Mode order n of standing wave SW: 1

(79) Vibration film **42**: two-layer structure of SiO.sub.2 film and ZrO.sub.2 film

(80) Film thickness t1 of SiO.sub.2 film: 0.35 μm

(81) Film thickness t2 of ZrO.sub.2 film: 0.15 μm

(82) Young's modulus E.sub.1 of SiO.sub.2: 75 GPa

(83) Young's modulus E.sub.2 of ZrO.sub.2: 190 GPa

(84) Sound velocity C.sub.1 of SiO.sub.2: 5900 m/s

(85) Sound velocity C.sub.2 of ZrO.sub.2: 4650 m/s

$$0.5 \times 10^{-6} \, (m) \leq t < 685 \times 10^{-6} \, (m) \qquad (14)$$

Arrangement of Ultrasonic Element **44**

(86) When the standing wave SW in the Y direction is generated inside the flow path **20**, an antinode A at which an acoustic pressure becomes maximum and a node N at which the acoustic pressure becomes 0 periodically appear along the Y direction. In the present embodiment, the antinode A appears at each of both end portions of the flow path **20** in the Y direction.

(87) For example, as shown in FIG. **2**, when the standing wave SW of the first-order mode is generated, the node N appears at a center portion of the flow path **20** in the Y direction, and the antinode A appears at each of both end portions of the flow path **20** in the Y direction. In this case, in the process of the fine particles M dispersed in the fluid S flowing through the flow path **20**, the fine particles M are converged to a range corresponding to the node N of the standing wave SW, that is, the center portion of the flow path **20** in the Y direction (acoustic convergence).

(88) Here, the flow path **20** is divided into, in the Y direction, a node region RN corresponding to the node N of the standing wave SW and antinode regions RA corresponding to the antinodes A of the standing wave SW.

(89) When the flow path width of the flow path **20** is L and the mode order of the standing wave SW is n, each node region RN is in a range from a center of each node N to ±L/4n in the Y direction, and each antinode region RA is in a range other than the range of the node region RN.

(90) With respect to the flow path **20** divided into the regions in this way, the ultrasonic element **44**, specifically, the fluid contact surface **422** of the vibrator **421** faces any antinode region RA in the Z direction. In other words, the opening portion **411** of the element substrate **41** opens toward the antinode region RA.

(91) Depending on a size of the ultrasonic element **44**, the ultrasonic element **44** may be present not only in the antinode region RA but also in the node region RN. However, it is desirable that the vibrator **421** not face the node N.

(92) FIG. **2** shows the standing wave SW of the first-order mode, but the standing wave SW generated in the present embodiment may be any standing wave of an order mode equal to or greater than the first-order mode.

(93) Effects of Present Embodiment

(94) As described above, the fluid device **10** according to the present embodiment includes the flow path **20** through which the fluid S flows, and the ultrasonic element **44** that transmits ultrasonic waves to the fluid S to generate the standing wave SW in the fluid S in the flow path **20** along a first direction (Y direction) orthogonal to the flowing direction of the fluid S. The ultrasonic element **44** includes the vibrator **421** having the fluid contact surface **422** that comes into contact with the fluid S, and the piezoelectric element **43** that is provided at the vibrator **421** and that flexurally vibrates the vibrator **421** in the normal direction of the fluid contact surface **422**. Further, when the thickness [m] of the vibrator **421** is t, the sound velocity [m/s] of the medium of the fluid S is C, the sound velocity [m/s] of the longitudinal wave of the vibrator **421** is C′, the dimension

[m] of the flow path **20** in the Y direction is L, and the mode order of the standing wave SW is n, the fluid device **10** satisfies the following expression (6).

(95) $t < \frac{C'}{C} \times \frac{L}{2n}$ (6)

(96) In such a configuration, since the fluid contact surface **422** of the vibrator **421** is in contact with the fluid S, the flow path substrate **30** is not interposed in a propagation path of the ultrasonic wave from the ultrasonic element **44** to the fluid S. That is, the ultrasonic wave is directly transmitted from the ultrasonic element **44** to the fluid S.

(97) The thickness of the vibrator **421** in contact with the fluid S is formed in a range of the above expression (6), so that the generation of the longitudinal wave in the vibrator **421** and the propagation of the longitudinal wave from the vibrator **421** to the fluid S are prevented.

(98) According to the above configuration, the matching of the acoustic impedances between the vibrator **421** of the ultrasonic element **44** and the fluid S in contact with the vibrator **421** is achieved, so that propagation efficiency of the ultrasonic wave from the ultrasonic element **44** to the fluid S can be improved. Accordingly, a drive voltage and the driving frequency that are applied to the piezoelectric element **43** can be set to be lower than those in the related art, and the width of the flow path **20** in which the standing wave SW is generated can be wider than that in the related art. As a result, a volume flow rate of the fluid S that can be treated using the fluid device **10** can be increased.

(99) When the dimension [m] of the vibrator **421** in the short-side direction is W, the average Young's modulus [Pa] of the vibration film when the Poisson's ratio is 0.3 is E′, and the sound velocity [m/sec] of the medium of the fluid is C, the fluid device **10** according to the present embodiment satisfies the following expression (10).

(100) $8.03 \times 10^{-3} \times W \times E'^{-\frac{1}{3}} \times (\frac{n}{2} \times \frac{C}{L}) \leqq t$ (10)

(101) According to such a configuration, by forming the vibrator **421** as thin as possible, the vibrator **421** can be prevented from being damaged when the piezoelectric element **43** is driven while the propagation efficiency of the ultrasonic wave from the ultrasonic element **44** to the fluid S is improved.

(102) In the fluid device **10** according to the present embodiment, the vibrator **421** faces the antinode region RA corresponding to any antinode A in the standing wave SW.

(103) According to such an arrangement, the propagation efficiency of the ultrasonic wave from the ultrasonic element **44** to the fluid S can be further improved.

(104) In the fluid device **10** according to the present embodiment, the dimension (flow path depth) H of the flow path **20** in the Z direction (second direction orthogonal to each of the flowing direction and the first direction) is smaller than the dimension (flow path width) of the flow path **20** in the Y direction.

(105) Accordingly, the generation of the standing wave in the Z direction can be prevented, and the standing wave SW in the Y direction can be suitably generated.

Second Embodiment

(106) Next, a second embodiment will be described.

(107) FIG. **3** is a cross-sectional view schematically showing a part of a fluid device **10**A according to the second embodiment, and FIG. **4** is a cross-sectional view taken along a line B-B in FIG. **3**.

(108) The fluid device **10**A according to the second embodiment has substantially the same configuration as the fluid device **10** according to the first embodiment except for the arrangement of the ultrasonic wave generation unit **40** with respect to the flow path substrate **30**.

(109) In the following description, the same components as the first embodiment are denoted by the same reference numerals, and the description thereof will be omitted or simplified.

(110) In the second embodiment, a through hole **331** penetrating the side wall portion **33** in the Y direction is formed in the flow path substrate **30**.

(111) The ultrasonic wave generation unit **40** is provided at the flow path substrate **30** so as to close

the through hole **331** of the side wall portion **33**, thereby forming a part of the wall portion of the flow path **20**. The ultrasonic element **44** is disposed such that the thickness direction of the vibrator **421** is along the Y direction, and the vibrator **421** faces the antinode region RA of the flow path **20** in the Y direction.

(112) Effects of Second Embodiment

(113) According to the above-described second embodiment, the same effects as the fluid device **10** according to the first embodiment can be achieved.

(114) In the second embodiment, since the ultrasonic element **44** is disposed such that the thickness direction of the vibrator **421** is along the Y direction, the main transmission direction of the ultrasonic wave from the ultrasonic element **44** coincides with the propagation direction of the ultrasonic wave combining the standing waves SW in the flow path **20**. Accordingly, it is possible to further improve the generation efficiency of the standing wave SW.

Third Embodiment

(115) Next, a third embodiment will be described.

(116) FIG. **5** is a cross-sectional view schematically showing a part of a fluid device **10**B according to the third embodiment, and FIG. **6** is a cross-sectional view taken along a line C-C in FIG. **5**.

(117) The fluid device **10**B according to the third embodiment has substantially the same configuration as the fluid device **10**A according to the second embodiment except that a pressure chamber **51** and a communication path **52** are interposed between the ultrasonic wave generation unit **40** and the flow path **20**.

(118) In the following description, the same components as the first and the second embodiments are denoted by the same reference numerals, and the description thereof will be omitted or simplified.

(119) The pressure chamber **51** is a storage chamber of the fluid S formed in the flow path substrate **30**, and is spaced apart from the flow path **20** in the Y direction. In the present embodiment, the pressure chamber **51** is formed in the side wall portion **33** on one side of the flow path **20** in the Y direction, and may be formed in the side wall portion **34** on the other side of the flow path **20** in the Y direction.

(120) The communication path **52** is a flow path that is formed inside the side wall portion **33** of the flow path substrate **30** and communicates the pressure chamber **51** with the flow path **20**. The communication path **52** is formed along the Y direction and is coupled to a side portion of the flow path **20**.

(121) The flow path **20** is coupled to the pressure chamber **51** via the communication path **52**, and the fluid S flowing through the flow path **20** flows into the pressure chamber **51**. The pressure chamber **51** is filled with the fluid S.

(122) In FIGS. **5** and **6**, two communication paths **52** are provided, and each communication path **52** communicates the pressure chamber **51** with the flow path **20**. However, the number of communication paths **52** is not limited to two, and may be one or more.

(123) A through hole **332** that connects the pressure chamber **51** and the outside in the Y direction is formed in a portion of the side wall portion **33** of the flow path substrate **30**. The portion is a wall portion of the pressure chamber **51**. The ultrasonic wave generation unit **40** is provided at the flow path substrate **30** so as to close the through hole **332**, thereby forming a part of the wall portion of the pressure chamber **51**. The element substrate **41** is disposed in the through hole **332** of the flow path substrate **30** such that the thickness direction of the element substrate **41** is along the Y direction, and the outer peripheral surface of the element substrate **41** is in liquid-tight contact with an inner peripheral surface of the through hole **332** of the flow path substrate **30**.

(124) Here, the ultrasonic element **44** is disposed such that the thickness direction of the vibrator **421** is along the Y direction, and the vibrator **421** faces the antinode region RA of the flow path in the Y direction via the pressure chamber **51** and the communication path **52**. The fluid contact surface **422** of the vibrator **421** is in contact with the fluid S in the pressure chamber **51**.

(125) Since the standing wave is generated in the fluid S in the flow path **20**, and the standing wave is not generated in the fluid S in the communication path **52** and the pressure chamber **51**, the fluid device **10**B according to the third embodiment satisfy the following expression (15).

(126) $Lr + Lp \neq \frac{L \times M}{n}$ (15)

(127) In the above expression (15), Lr is a dimension [m] of the communication path **52** in the Y direction, Lp is a dimension [m] of the pressure chamber **51** in the Y direction, M is a natural number, n is the mode order of the standing wave SW, and L is the dimension (flow path width) [m] of the flow path **20** in the Y direction.

(128) The fluid device **10**B according to the third embodiment satisfies the following expressions (16) to (18).

(129) $w_r < 4 \times L \times n^{-\frac{1}{2}}$ (16) $W_r \leqq 0.3 \times d_r$ (17) $\frac{Sr \times L}{n} \geqq \quad \times Sb$ (18)

(130) In the above expressions (16), (17), W.sub.r is a width [m] of the communication path **52** in the X direction, L is the flow path width [m], n is the mode order of the standing wave SW, and d.sub.r is a depth [m] of the communication path **52** in the Z direction.

(131) In a case where the above expressions (16), (17) are satisfied, when an ultrasonic wave emitted from the communication path **52** into the flow path **20** is reflected by a wall surface of the flow path **20** and returns to the communication path **52**, a beam width of the ultrasonic wave becomes larger than the width W.sub.r of the communication path **52**. That is, the beam width of the ultrasonic wave spreads wider than the width W.sub.r of the communication path **52**.

(132) In the above expression (18), Sr is a flow path cross-sectional area [m.sup.2] of all the communication paths **52** orthogonal to the Y direction, L is the flow path width [m], n is the mode order of the standing wave SW, Sb is an area [m.sup.2] of the fluid contact surface **422** of the vibrator **421**, and **5** is a displacement amount [m] of the vibrator **421** at the time of the vibration.

(133) When the expression (18) is satisfied, a value obtained by dividing a volume of a range in the flow path **20** facing the communication path **52** in the Y direction by the mode order n of the standing wave SW is equal to or greater than a maximum variation amount of a volume of the pressure chamber **51** caused by the flexural vibration of the vibrator **421**.

(134) Effects of Third Embodiment

(135) According to the above-described third embodiment, the same effects as the fluid device **10** according to the first embodiment and the fluid device **10**A according to the second embodiment can be achieved.

(136) Here, in the first to third embodiments, since the vibrator **421** faces the fluid S, the ultrasonic element **44** directly transmits ultrasonic waves to the fluid S. The ultrasonic wave transmitted in the fluid S forms the standing wave SW by being reflected by the wall surface of the flow path **20** while the acoustic power is not substantially attenuated.

(137) In the first embodiment and the second embodiment described above, since the vibrator **421** faces the fluid S in the flow path **20**, the ultrasonic wave reflected in the flow path **20** directly returns to the vibrator **421**. Therefore, unless the ultrasonic element **44** transmits an ultrasonic wave having an acoustic power equal to or higher than an initially applied acoustic power, the ultrasonic element **44** may be defeated by the reflected and returned ultrasonic wave, and it is difficult to superimpose the acoustic power of the ultrasonic wave in the flow path **20**. That is, the acoustic power of the ultrasonic wave in the flow path **20** is determined by an acoustic power of a first transmitted ultrasonic wave, and it is difficult to add the acoustic power.

(138) On the other hand, the fluid device **10**B according to the third embodiment further includes the pressure chamber **51** that stores the fluid S, and the communication path **52** that is formed along the Y direction and that communicates the flow path **20** with the pressure chamber **51**, and the ultrasonic element **44** is disposed such that the fluid contact surface **422** of the vibrator **421** is in contact with the fluid S in the pressure chamber **51**.

(139) According to the third embodiment, a part of the ultrasonic wave reflected by the wall surface

of the flow path **20** returns to the vibrator **421** via the communication path **52**, but a remaining part of the ultrasonic wave is reflected again by the wall surface of the flow path **20**. That is, it is possible to reduce a proportion of the ultrasonic wave returning to the vibrator **421**. Therefore, the ultrasonic wave transmitted by the ultrasonic element **44** is not defeated by the ultrasonic wave returning to the vibrator **421** via the communication path **52**, and the pressure in the pressure chamber **51** is increased, so that the acoustic power can be added to the inside of the flow path **20**. Accordingly, it is easy to generate the standing wave SW having a higher acoustic power.

(140) In particular, the fluid device **10**B according to the third embodiment satisfies the above expressions (16), (17), so that the beam width of the ultrasonic wave is larger than the width W.sub.r of the communication path **52**. Therefore, the effect of reducing the proportion of the ultrasonic wave returning to the vibrator **421** can be suitably exhibited.

(141) Further, in the third embodiment, the fluid device **10**B is formed such that the above expression (18) is established. Here, the value obtained by dividing the volume of the range in the flow path **20** facing the communication path **52** in the Y direction by the mode order n of the standing wave SW corresponds to a volume variation of a medium in the communication path **52**. When the value is equal to or larger than the maximum variation amount of the volume of the pressure chamber **51** caused by the flexural vibration of the vibrator **421**, the volume variation of the medium in the pressure chamber **51** due to deformation of the vibration film **42** is discharged as a volume variation of a medium in the communication path **52**, and thus it is possible to prevent the pressure increase in the pressure chamber **51**. Therefore, it is possible to prevent the vibration film **42** and the piezoelectric element **43** from being damaged.

(142) Modifications

(143) The present disclosure is not limited to the embodiment described above, and configurations obtained through modifications, alterations, and appropriate combinations of the embodiments within a scope of being capable of achieving the object of the present disclosure are included in the present disclosure.

(144) First Modification

(145) In each of the above embodiments, the examples are described in which one ultrasonic element **44** is provided in the fluid devices **10**, **10**A, **10**B. However, a plurality of ultrasonic elements **44** may be provided in the fluid devices **10**, **10**A, **10**B.

(146) For example, a plurality of opening portions **411** are formed in an array for the element substrate **41**, and a portion of the vibration film **42** provided at the element substrate **41** overlapping each opening portion **411** may constitute the vibrator **421**. In this case, the plurality of ultrasonic elements **44** are formed by providing the piezoelectric element **43** for each vibrator **421**.

(147) A plurality of ultrasonic wave generation units **40** as described in each of the above embodiments may be provided.

(148) In the above-described third embodiment, when the plurality of ultrasonic elements **44** are provided, Sb in the above expression (18) is a total area of the fluid contact surfaces **422** of the plurality of ultrasonic elements **44**.

(149) Second Modification

(150) In the first embodiment and the second embodiment, the example is described in which the ultrasonic element **44** is disposed for one antinode region RA of the standing wave SW formed in the flow path **20**. However, the ultrasonic element **44** may be disposed for each of two or more antinode regions RA.

(151) However, in the antinodes A appearing on both sides of the node N of the standing wave SW, phases of pressure waveforms are opposite to each other.

(152) Therefore, it is desirable to reverse a phase of a driving frequency between the ultrasonic element **44** disposed for the antinode region RA corresponding to one antinode A and the ultrasonic element **44** disposed for the antinode region RA corresponding to the other antinode A.

(153) Third Modification

(154) In the third embodiment, the ultrasonic element **44** is disposed such that the thickness direction of the vibrator **421** is along the Y direction. However, the present disclosure is not limited thereto.

(155) For example, in the third embodiment, the through hole in the Z direction may be formed in the portion of the flow path substrate **30** that is the wall portion of the pressure chamber **51**, the ultrasonic wave generation unit **40** may be provided so as to close the through hole, and the ultrasonic element **44** may be disposed such that the thickness direction of the vibrator **421** is along the Z direction.

(156) In this case, a component of the ultrasonic wave transmitted from the ultrasonic element **44** that has an angle with respect to the Z direction is directed to the flow path **20** via the communication path **52**, and is repeatedly reflected by the inner walls of the flow path **20**, so that the standing wave SW in the Y direction is generated in the flow path **20**.

(157) Fourth Modification

(158) The specific configuration of the ultrasonic wave generation unit **40** described in each of the above embodiments can be modified in various ways.

(159) For example, the element substrate **41** may be disposed outside the through hole **311** of the flow path substrate **30**. In this case, the opening portion **411** of the element substrate **41** overlaps the through hole **311** of the flow path substrate **30**, and a lower surface of the element substrate **41** is in liquid-tight contact with an upper surface of the flow path substrate **30**.

(160) The ultrasonic wave generation unit **40** may not include the element substrate **41**, and the vibration film **42** may be provided at the flow path substrate **30**. In this case, a portion of the vibration film **42** overlapping the through holes **311**, **331** of the flow path substrate **30** constitutes the vibrator **421**.

(161) Fifth Modification

(162) In each of the above embodiments, the standing wave SW is generated in the width direction (Y direction) of the flow path **20** as one direction orthogonal to the flowing direction of the fluid S. However, the standing wave SW may be generated in the depth (Z direction) of the flow path **20**. In this case, a configuration can be applied in which the Y direction and the Z direction that are described in the above embodiments are appropriately replaced with each other.

(163) Overview of Present Disclosure

(164) A fluid device according to an aspect of the present disclosure includes: a flow path through which a fluid flows; and an ultrasonic element configured to transmit an ultrasonic wave to the fluid to generate a standing wave in the fluid in the flow path along a first direction orthogonal to a flowing direction of the fluid. The ultrasonic element includes a vibrator having a fluid contact surface that comes into contact with the fluid, and a piezoelectric element that is provided at the vibrator and that is configured to flexurally vibrate the vibrator in a normal direction of the fluid contact surface. When a thickness of the vibrator in the normal direction is t, a sound velocity of a medium of the fluid is C, an average sound velocity of a longitudinal wave transmitted in the vibrator is C′, a dimension of the flow path in the first direction is L, and a mode order of the standing wave is n, the following expression is satisfied.

(165) $t < \frac{C'}{C} \times \frac{L}{2n}$

(166) In such a configuration, since the fluid contact surface of the vibrator comes into contact with the fluid, another member is not interposed in a propagation path of the ultrasonic wave from the ultrasonic element to the fluid. That is, the ultrasonic wave is directly transmitted from the ultrasonic element to the fluid.

(167) The thickness of the vibrator in contact with the fluid is formed in a range of the above expression, so that generation of the longitudinal wave in the vibrator and propagation of the longitudinal wave from the vibrator to the fluid are prevented.

(168) According to the above configuration, matching of acoustic impedances between the vibrator of the ultrasonic element and the fluid in contact with the vibrator is achieved, so that propagation

efficiency of the ultrasonic wave from the ultrasonic element to the fluid can be improved. Accordingly, a drive voltage and a driving frequency that are applied to the piezoelectric element can be set to be lower than those in the related art, and a width of the flow path in which the standing wave is generated can be wider than that in the related art. As a result, a volume flow rate of the fluid that can be treated using the fluid device can be increased.

(169) In the fluid device according to the present aspect, when a dimension of the vibrator in a short-side direction orthogonal to the normal direction is W, an average Young's modulus of the vibrator when a Poisson's ratio is 0.3 is E′, and the sound velocity of the medium of the fluid is C, the following expression is satisfied.

(170) $08.03 \times 10^{-3} \times W \times E'^{-\frac{1}{3}} \times (\frac{n}{2} \times \frac{C}{L}) \leqq t$

(171) According to such a configuration, by forming the vibrator as thin as possible, the vibrator can be prevented from being damaged when the piezoelectric element is driven while the propagation efficiency of the ultrasonic wave from the ultrasonic element to the fluid is improved.

(172) In the fluid device according to the present aspect, the vibrator faces an antinode region corresponding to any antinode in the standing wave.

(173) According to such an arrangement, the propagation efficiency of the ultrasonic wave from the ultrasonic element to the fluid can be further improved.

(174) In the fluid device according to the present aspect, the vibrator is disposed such that a thickness direction of the vibrator is along the first direction.

(175) Accordingly, a main transmission direction of the ultrasonic wave from the ultrasonic element coincides with a propagation direction of the ultrasonic wave combining the standing waves in the flow path, so that generation efficiency of the standing wave can be further improved.

(176) In the fluid device according to the present aspect, a dimension of the flow path in a second direction orthogonal to the flowing direction and the first direction is smaller than the dimension of the flow path in the first direction.

(177) Accordingly, generation of the standing wave in the second direction can be prevented, and the standing wave in the first direction can be suitably generated.

(178) The fluid device according to the present aspect further includes: a pressure chamber configured to store the fluid; and a communication path that is formed along the first direction and that communicates the flow path with the pressure chamber. The ultrasonic element is disposed such that the fluid contact surface is in contact with the fluid in the pressure chamber.

(179) According to such a configuration, the ultrasonic wave transmitted by the ultrasonic element is not defeated by the ultrasonic wave reflected in the flow path and returning to the vibrator via the communication path, and a pressure in the pressure chamber is increased, so that an acoustic power can be added to the inside of the flow path. Accordingly, it is easy to generate a standing wave having a higher acoustic power.

Claims

1. A fluid device, comprising: a flow path substrate with a flow path through which a fluid flows; and a plurality of ultrasonic elements having a first ultrasonic element and a second ultrasonic element, and the plurality of ultrasonic elements are configured to transmit an ultrasonic wave of a plurality of ultrasonic waves, and to generate a standing wave in the fluid in the flow path along a first direction orthogonal to a flowing direction of the fluid, wherein each of the plurality of ultrasonic elements includes: an element substrate with a plurality of first opening portions, wherein the plurality of first opening portions are formed in an array for the element substrate, the plurality of first opening portions penetrate the element substrate along a thickness direction of the element substrate, and an outer peripheral surface of the element substrate is in contact with an inner peripheral surface of a second opening portion of the flow path substrate; a vibrator supported

by the element substrate and overlapping each of the plurality of the first opening portions, wherein the first ultrasonic element is disposed on an opening portion of the plurality of first opening portions for a first antinode region corresponding to a first antinode of the standing wave, the second ultrasonic element is disposed on another opening portion of the plurality of first opening portions for a second antinode region corresponding to a second antinode of the standing wave, the opening portion of the plurality of first opening portions and the other opening portion of the plurality of first opening portions are different, a phase of a driving frequency of a second ultrasonic wave of the second ultrasonic element is opposite to a phase of a driving frequency of a first ultrasonic wave of the first ultrasonic element, the vibrator has a fluid contact surface that is in contact with the fluid, and the vibrator closes each of the plurality of the first opening portions of the element substrate; and a piezoelectric element that is provided at the vibrator and that is configured to generate flexural vibration to the vibrator in a normal direction of the fluid contact surface, wherein $t < \frac{C'}{C} \times \frac{L}{2n}$ wherein a thickness of the vibrator in the normal direction is t, a sound velocity of the fluid is C, an average sound velocity of a longitudinal wave transmitted in the vibrator is C', a dimension of the flow path in the first direction is L, and a mode order of the standing wave is n.

2. The fluid device according to claim 1, wherein $8.03 \times 10^{-3} \times W \times E'^{-\frac{1}{3}} \times (\frac{n}{2} \times \frac{C}{L}) \leqq t$ wherein a dimension of the vibrator in a direction orthogonal to the normal direction is W, an average Young's modulus of the vibrator when a Poisson's ratio is 0.3 is E', and the sound velocity of the fluid is C.

3. The fluid device according to claim 1, wherein the vibrator is disposed on regions corresponding to the first antinode and the second antinode of the standing wave.

4. The fluid device according to claim 1, wherein the vibrator is disposed such that the normal direction of the fluid contact surface is along the first direction.

5. The fluid device according to claim 1, wherein a dimension of the flow path in a second direction orthogonal to the flowing direction and the first direction is smaller than the dimension of the flow path in the first direction.

6. The fluid device according to claim 2, wherein a dimension of the flow path in a second direction orthogonal to the flowing direction and the first direction is smaller than the dimension of the flow path in the first direction.

7. The fluid device according to claim 3, wherein a dimension of the flow path in a second direction orthogonal to the flowing direction and the first direction is smaller than the dimension of the flow path in the first direction.

8. The fluid device according to claim 4, wherein a dimension of the flow path in a second direction orthogonal to the flowing direction and the first direction is smaller than the dimension of the flow path in the first direction.

9. The fluid device according to claim 1, further comprising: a pressure chamber configured to store the fluid; and a communication path that is formed along the first direction and that communicates the flow path with the pressure chamber, wherein the plurality of ultrasonic elements are disposed such that the fluid contact surface is in contact with the fluid in the pressure chamber.