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(54) **SYSTEM AND METHOD FOR DETERMINING VELOCITY OF ELECTRICALLY CONDUCTIVE FLUID**

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(51) **Int. Cl.**
G01F 1/708 (2006.01)

(52) **U.S. Cl.** **73/861.95**

(58) **Field of Classification Search** 73/861.95, 73/861.17, 202.5, 861.05
See application file for complete search history.

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(57) **ABSTRACT**

A flowing electrically-conductive fluid is controlled between an upstream and downstream location thereof to insure that a convection timescale of the flowing fluid is less than a thermal diffusion timescale of the flowing fluid. First and second nodes of a current-carrying circuit are coupled to the fluid at the upstream location. A current pulse is applied to the current-carrying circuit so that the current pulse travels through the flowing fluid to thereby generate a thermal feature therein at the upstream location. The thermal feature is convected to the downstream location where it is monitored to detect a peak associated with the thermal feature so-convected. The velocity of the fluid flow is determined using a time-of-flight analysis.

20 Claims, 2 Drawing Sheets

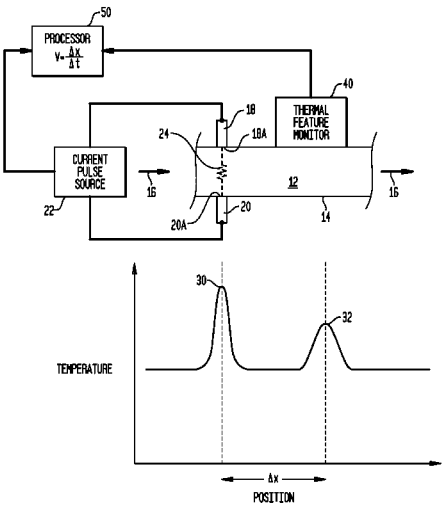


FIG. 1

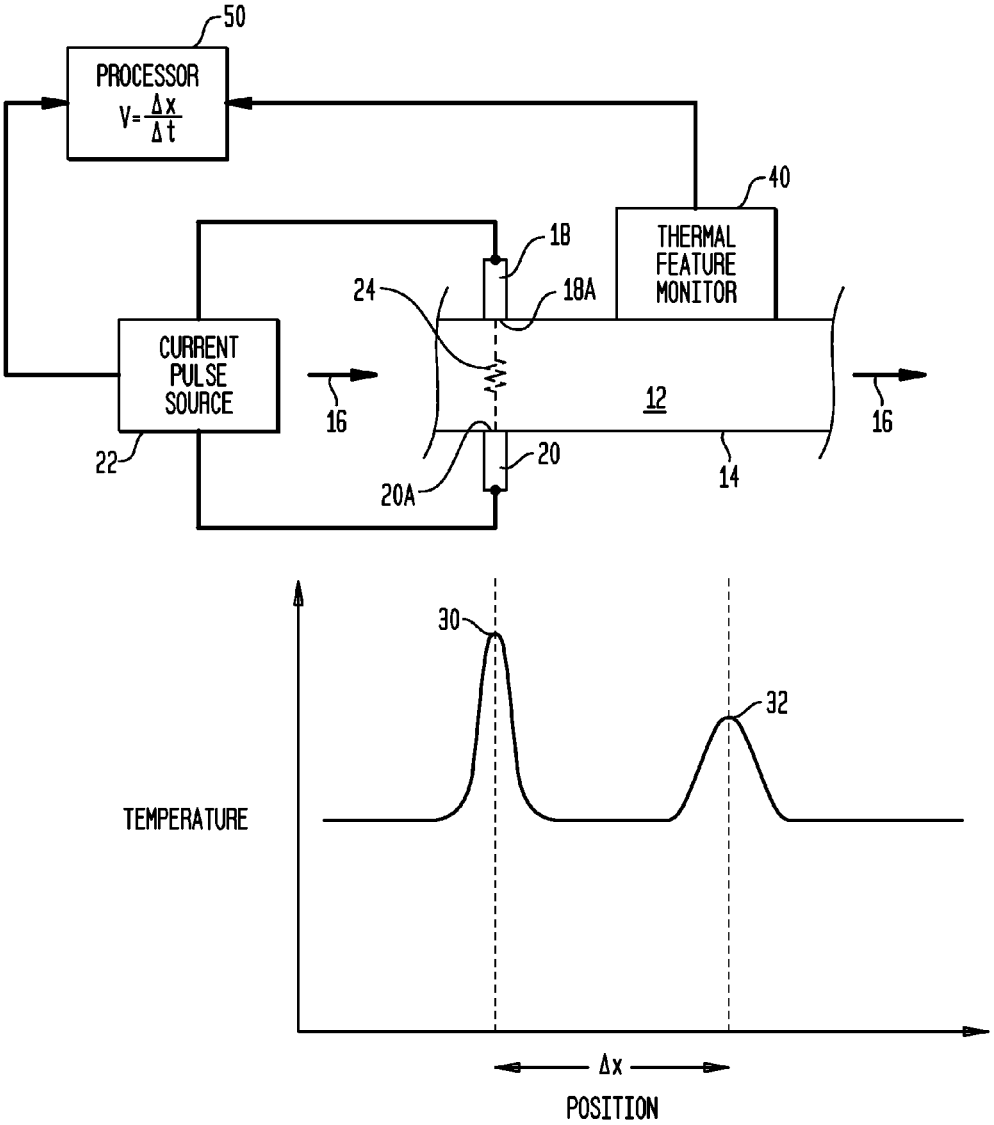

50
PROCESSOR
V= Δx/Δt
40
THERMAL FEATURE MONITOR
18
18A
24
CURRENT PULSE SOURCE
16
12
16
22
20
20A
14
30
32
TEMPERATURE
Δx
POSITION

FIG. 2

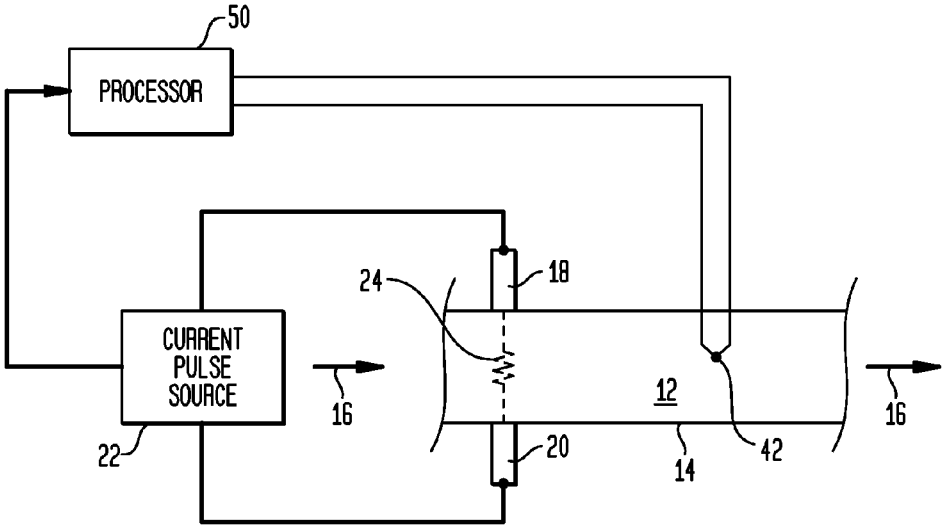
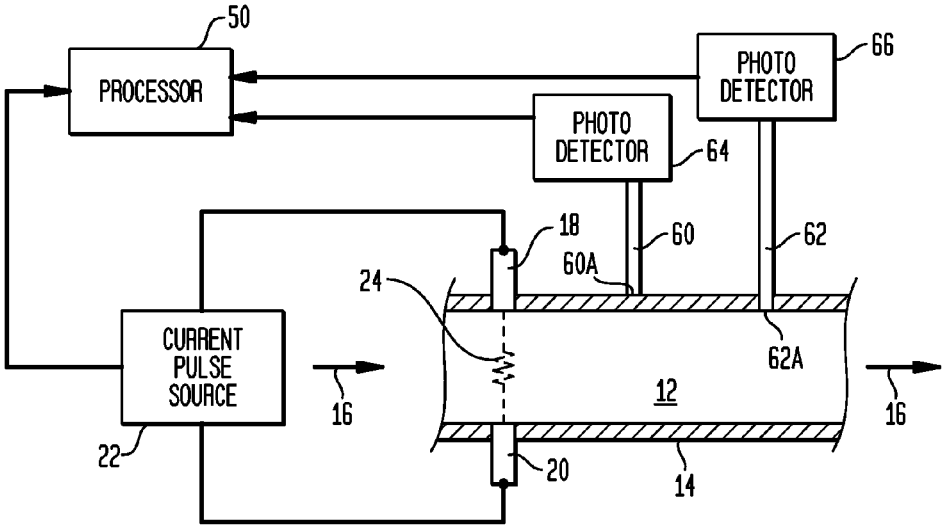

50
PROCESSOR
CURRENT PULSE SOURCE
22
24
18
20
16
12
14
42
16

FIG. 3


50
PROCESSOR
PHOTO DETECTOR
66
PHOTO DETECTOR
64
18
60
62
60A
24
CURRENT PULSE SOURCE
62A
12
16
16
22
20
14

SYSTEM AND METHOD FOR DETERMINING VELOCITY OF ELECTRICALLY CONDUCTIVE FLUID

CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application Ser. No. 60/877,015 filed on Dec. 4, 2006.

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and by an employee of the United States Government and is subject to the provisions of Public Law 96-517 (35 U.S.C §202) and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefore. In accordance with 35 U.S.C §202, the contractor elected not to retain title.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to fluid flow measurements. More specifically, the invention is a system and method for determining the velocity of an electrically conductive fluid.

2. Description of the Related Art

Measuring the velocity of a moving fluid is important or required for a variety of applications. Some applications require a high-degree of measurement precision. For example, the flow velocity of liquid metal propellants (e.g., molten bismuth) in an electric propulsion system must be measured/determined with a high-degree of mass-flow resolution. Further, the system for making such a velocity measurement/determination must be able to withstand temperatures of the liquid (i.e., molten) metal.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a method and system for determining the velocity of a flowing liquid metal.

Another object of the present invention is to provide a method and system for determining the velocity of a molten propellant such as molten bismuth.

Still another object of the present invention is to provide a method and system for determining the velocity of a flowing liquid metal with minimal intrusion on the flowing liquid metal.

Other objects and advantages of the present invention will become more obvious hereinafter in the specification and drawings.

In accordance with the present invention, a method and system are provided for determining velocity of a flowing electrically conductive fluid with a finite resistivity. The flowing fluid is controlled between an upstream and downstream location thereof to insure that a convection timescale of the flowing fluid is less than a thermal diffusion timescale of the flowing fluid between the upstream and downstream locations. First and second nodes of a current-carrying circuit are coupled to the fluid at the upstream location so that the flowing fluid passes therebetween. A current pulse is applied to the current-carrying circuit. As a result, the current pulse travels through the flowing fluid to thereby generate a thermal feature in the flowing fluid at the upstream location. The thermal feature is convected to the downstream location where it is monitored to detect a peak associated with the thermal feature so-convected. The velocity of the fluid flow is determined using (i) the distance between the upstream and downstream locations, and (ii) the time between the application of the current pulse to the current-carrying circuit and detection of the peak at the downstream location.

BRIEF DESCRIPTION OF THE DRAWING(S)

Other objects, features and advantages of the present invention will become apparent upon reference to the following description of the preferred embodiments and to the drawings, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

FIG. **1** is a schematic diagram of a system for determining velocity of a conductive fluid and a corresponding graph of a thermal feature generated and detected by the system in accordance with the method of the present invention;

FIG. **2** is a schematic diagram of an embodiment of the system utilizing a thermocouple to detect the thermal feature; and

FIG. **3** is a schematic diagram of another embodiment of the system utilizing optical detection of the thermal feature.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

Referring now to the drawings and more particularly to FIG. **1**, a system for determining the velocity of a flowing electrically conductive fluid is shown and is referenced generally by numeral **10**. It is to be understood that the present invention can be used to determine the velocity of any electrically-conductive fluid that also has a characteristic electrical resistance. For example, the fluid can be molten bismuth which is used as a propellant for Hall thrusters.

For purpose of the present invention, a fluid **12** whose velocity is to be determined is confined to a flow volume that is typically defined by a conduit **14**. The flow of fluid **12** through conduit **14** is in the direction indicated by arrows **16**. Passing through conduit **14** on either side thereof are the tips **18**A and **20**A of two electrodes **18** and **20**, respectively. Ideally, tips **18**A and **20**A are flush with the inside wall of conduit **14** so as not to obstruct the flow of fluid **12**. Further, tips **18**A and **20**A are typically diametrically opposed to one another to define an imaginary line extending through fluid **12** that is perpendicular to flow direction **16**. Coupled to electrodes **18** and **20** is a current pulse source **22** (e.g., a capacitor discharge) capable of generating a brief (e.g., typically less than 1 millisecond) current pulse that transits fluid **12**. That is, the combination of current pulse source **22**, electrodes **18** and **20**, and fluid **12**, essentially define an electrical circuit with fluid **12** acting as an electrical resistance element disposed between circuit nodes defined by electrode tips **18**A and **20**A.

The electrical resistance element is indicated by dashed line **24** in the drawings. Accordingly, when a current pulse is applied to either electrode **18** or electrode **20**, the current pulse exits the corresponding electrode tip, transits fluid **12**, and is coupled to the other opposing electrode tip nearly instantaneously in time. Since fluid **12** is electrically resistive, the current pulse will generate a corresponding and instantaneous increase in thermal energy, i.e., a narrow region of increased fluid temperature that peaks along an imaginary line extending between electrode tips **18**A and **20**A. This temperature peak or spike is indicated by reference numeral **30** in the graph of temperature versus position aligned with conduit **14**. The resulting pulse of thermal energy in fluid **12**

forms a thermal feature in fluid **12**. Using a conventional "time-of-flight" analysis, the time "Δt" it takes for this thermal feature to travel a known distance "Δx" in conduit **14** is indicative of the velocity "V" of fluid **12**.

Detection of the thermal feature at a downstream location along conduit **12** is accomplished by a thermal feature monitor **40** that is located a distance Δx downstream from electrodes **18** and **20**. While it is expected that the peak temperature "T_{P0}" of the thermal feature at the creation thereof will be greater than the peak temperature T_{P1}" of the thermal feature after traveling a distance Δx downstream, the present invention requires that the spatial integrity of the thermal feature be maintained so that peak temperature T_{P1} can be detected. That is, the spatial integrity of the thermal feature must be maintained as it propagates from electrodes **18** and **20** to monitor **40** so that a reduced thermal feature peak **32** can be detected. In this way, the time of-flight between the two locations can be accurately determined. Accordingly, the convection timescale "τ_C" of the fluid flow system should be small relative to the thermal diffusion timescale "τ_D" of the fluid flow system. The convection timescale τ_C is the ratio of the characteristic device length "L" (i.e., the distance Δx between electrodes **18**/**20** and monitor **40**) to the characteristic flow speed "u" or τ_C=L/u. The thermal diffusion timescale TD is governed by the thermal diffusivity "a" of fluid **12** and the characteristic length of a temperature gradient (which is the characteristic device length L in the instant case) where $\tau_D=L^2/\alpha$. In the present invention, the structure of system **10** (e.g., conduit diameter, the distance Δx, etc.) is designed such that $\tau_C<\tau_D$ to insure that the generated thermal feature is convected downstream with a peak that remains intact and is detectable by monitor **40**.

A processor **50** is coupled to current pulse source **22** and monitor **40** to track the time Δt between (i) the application of the current pulse to electrodes **18** and **20** at time t_0, and (ii) the detection of peak **32** by monitor **40** at time t_1. Since the propagation distance Δx is known, the velocity V of fluid **12** is readily determined by processor **50** using a conventional time-of-flight calculation.

Thermal feature monitor **40** can be realized using a simple temperature sensor (FIG. **2**) or by using optical techniques (FIG. **3**) when the temperature of the fluid is high (i.e., 300° C. or higher) such that the thermal feature produces thermal light emission (e.g., infra red emission) "visible" to photodiodes. In FIG. **2**, thermal feature monitoring at the downstream location is accomplished with a thermocouple **42** placed in fluid **12** as shown. The output of thermocouple **42** is provided to processor **50** which detects the time of occurrence of the thermal feature's peak (i.e., peak **32** described above).

In FIG. **3**, thermal feature monitoring is accomplished in an optical fashion. This arrangement/method of monitoring is particularly effective when fluid **12** is maintained at high temperature of 300° C. or greater. For example, this is the case for molten bismuth propellant that is fed to Hall thrusters. At such elevated fluid temperatures, thermal light emission can be monitored as follows. In general, FIG. **3** illustrates a differential-type monitoring system where reference and measurement signals are differenced in order to eliminate system noise. More specifically, a first optical fiber **60** has its end face **60**A coupled to the exterior surface of conduit **14**. A second optical fiber **62** passes through an exterior wall of conduit **14** such that its end face **62**A is aligned or is flush with the inside wall of conduit **14**. Optical fiber **60** terminates at its opposite end in a photo detector **64** that generates an electrical signal indicative of the thermal light emission of conduit **14** as well as system noise. The output of photo detector **64** serves as a reference signal provided to processor **50**. Optical fiber **62** monitors thermal light emission of fluid **12** as well as system noise. Optical fiber **62** terminates at its opposite end in a photo detector **66** that generates an electrical signal indicative of the thermal light emission of fluid **12** as well as system noise. The output of photo detector **66** is the measurement signal provided to processor **50**. The signals from detectors **64** and **66** are differenced to eliminate steady-state and correlated system noise so that the thermal feature's peak can be readily detected as it is convected past end face **62**A of optical fiber **62**.

The advantages of the present invention are numerous. The fluid whose velocity is to be determined serves as a resistive heating element thereby eliminating the need to place a heater in the fluid flow. Further, no steady-state heating of the fluid is required. The absolute temperature of the fluid is unimportant since the present invention need only generate/detect a thermal feature peak. The optical monitoring embodiment further provides the advantage of elevated temperature operation and the elimination of all velocity measurement equipment from the fluid flow.

Although the invention has been described relative to a specific embodiment thereof, there are numerous variations and modifications that will be readily apparent to those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. A method of determining velocity of a flowing fluid with the fluid being electrically conductive with finite resistivity, said method comprising the steps of:

controlling the flowing fluid between an upstream and downstream location thereof to insure that a convection timescale of the flowing fluid is less than a thermal diffusion timescale of the flowing fluid between said upstream and downstream locations;

coupling first and second nodes of a current-carrying circuit to the fluid at said upstream location wherein the flowing fluid passes between said first and second nodes;

applying a current pulse to the current-carrying circuit wherein said current pulse travels through the flowing fluid to thereby generate a thermal feature in the flowing fluid at said upstream location, and wherein said thermal feature is convected to said downstream location;

monitoring the fluid flow at said downstream location to detect a peak associated with said thermal feature so-convected; and

determining velocity of the fluid flow using (i) the distance between said upstream and downstream locations, and (ii) the time between said step of applying and detection of said peak.

2. A method according to claim **1** wherein said step of coupling comprises the step of positioning said first and second nodes of the current-carrying circuit such that said current pulse travels through the flowing fluid in a direction that is perpendicular to the flowing fluid's direction of movement.

3. A method according to claim **1** wherein the fluid is bismuth.

4. A method according to claim **1** wherein said step of monitoring comprises the step of detecting said peak using a thermocouple positioned in the flowing fluid.

5. A method according to claim **1** wherein said step of monitoring comprises the step of optically detecting said peak from a position adjacent the fluid flow.

6. A method according to claim **1** wherein the fluid has a temperature of at least 300° C., and wherein said step of

monitoring comprises the step of optically detecting thermal light emission associated with said thermal feature so-convected from a position adjacent the fluid flow.

7. A system for determining velocity of a flowing fluid with the fluid being electrically conductive with finite resistivity, comprising:

means for controlling the flowing fluid between an upstream and downstream location thereof to insure that a convection timescale of the flowing fluid is less than a thermal diffusion timescale of the flowing fluid between said upstream and downstream locations;

a current-carrying circuit having first and second nodes coupled to the fluid at said upstream location wherein the flowing fluid passes between said first and second nodes;

means for applying a current pulse to said current-carrying circuit wherein said current pulse travels through the flowing fluid to thereby generate a thermal feature in the flowing fluid at said upstream location, and wherein said thermal feature is convected to said downstream location;

means for monitoring the fluid flow at said downstream location to detect a peak associated with said thermal feature so-convected; and

processing means for determining velocity of the fluid flow using (i) the distance between said upstream and downstream locations, and (ii) the time between application of said current pulse to said current-carrying circuit and detection of said peak.

8. A system as in claim **7** wherein said first and second nodes of said current-carrying circuit are positioned such that said current pulse travels through the flowing fluid in a direction that is perpendicular to the flowing fluid's direction of movement.

9. A system as in claim **7** wherein the fluid is bismuth.

10. A system as in claim **7** wherein said means for monitoring comprises a thermocouple positioned in the flowing fluid.

11. A system as in claim **7** wherein said means for monitoring comprises means for optically detecting said peak from a position adjacent the fluid flow.

12. A system as in claim **7** wherein the fluid has a temperature of at least 300° C., and wherein said means for monitoring comprises means for optically detecting thermal light emission associated with said thermal feature so-convected from a position adjacent the fluid flow.

13. A system for determining velocity of a flowing fluid with the fluid being electrically conductive with finite resistivity, comprising:

a conduit for transporting the flowing fluid between an upstream and downstream location thereof, said conduit being sized to insure that a convection timescale of the flowing fluid is less than a thermal diffusion timescale of the flowing fluid between said upstream and downstream locations;

first and second electrodes coupled to the flowing fluid at first and second opposing nodes of said conduit at said upstream location wherein the flowing fluid passes between said first and second electrodes;

means for applying a current pulse to one of said first and second electrodes wherein said current pulse travels through the flowing fluid to thereby generate a thermal feature in the flowing fluid at said upstream location, and wherein said thermal feature is convected to said downstream location;

means for monitoring the fluid flow at said downstream location to detect a peak associated with said thermal feature so-convected; and

processing means for determining velocity of the fluid flow using (i) the distance between said upstream and downstream locations, and (ii) the time between application of said current pulse to one of said first and second electrodes and detection of said peak.

14. A system as in claim **13** wherein said first and second electrodes are positioned such that said current pulse travels through the flowing fluid in a direction that is perpendicular to the flowing fluid's direction of movement.

15. A system as in claim **13** wherein the fluid is bismuth.

16. A system as in claim **13** wherein said means for monitoring comprises a thermocouple positioned in the flowing fluid.

17. A system as in claim **13** wherein said means for monitoring comprises means for optically detecting said peak from a position adjacent the fluid flow.

18. A system as in claim **13** wherein the fluid has a temperature of at least 300° C., and wherein said means for monitoring comprises means for optically detecting thermal light emission associated with said thermal feature so-convected from a position adjacent the fluid flow.

19. A system as in claim **18** wherein said means for optically detecting said thermal light emission includes first and second optical detectors, said first optical detector including a reference optical fiber having an end coupled to said conduit at said downstream location, said second optical detector having a measurement optical fiber having an end exposed to the fluid flow at said downstream location, and wherein said thermal light emission associated with said thermal feature is indicated by a difference between outputs of said first and second optical detectors.

20. A system as in claim **19** wherein said end of said measurement optical fiber is aligned with an inside wall of said conduit.

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