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(74) Agents: JORIO, Paolo et al.; Studio Torta s.r.l., Via Viotti, 9, I-10121 Torino (IT).

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(71) Applicant (for all designated States except US): **PO-LITECNICO DI TORINO** [IT/IT]; Corso Duca degli Abruzzi 24, I-10129 Torino (TO) (IT).

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(72) Inventors; and

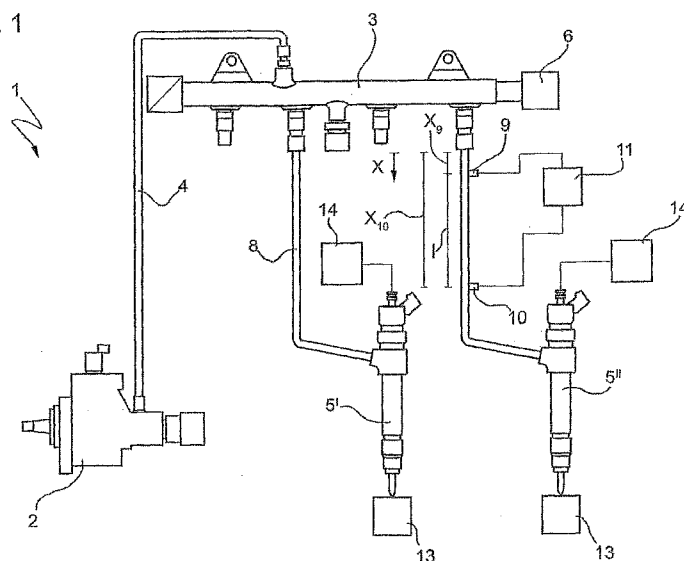
(75) Inventors/Applicants (for US only): **CATANIA, Andrea** Emilio [IT/IT]; Via Fidias, 22, I-10100 Torino (IT). **FER-RARI, Alessandro** [IT/IT]; Via Menabrea, 12, I-10100 Torino (IT).

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(54) Title: METHOD FOR DETERMINING THE INSTANTANEOUS FLOW RATE OF A FLUID, IN PARTICULAR FOR A LIQUID UNDER HIGH-PRESSURE

FIG. 1



(57) Abstract: A method for determining the instantaneous flow rate of a fluid in a pipeline (8) comprising the phases of : - measuring the difference in pressure of the fluid in at least two points of said pipeline (8) longitudinally set apart at a certain distance (1) to calculate the related pressure gradient, and - determining the instantaneous flow rate by using the value of the pressure gradient in a model based on a system of differential equations including the mass conservation equation and the momentum balance equation.

"METHOD FOR DETERMINING THE INSTANTANEOUS FLOW RATE OF A FLUID, IN PARTICULAR FOR A LIQUID UNDER HIGH-PRESSURE"

TECHNICAL FIELD

The present invention concerns a method for determining the instantaneous flow rate of a fluid, in particular for a liquid under high-pressure.

BACKGROUND ART

A liquid that flows under high pressure, that is between 50 and 2500 bar, can be used in engineering applications such as a high-pressure piston pump, a fuel injection system for a diesel engine, an anti-lock braking system (ABS) or a traction control system (TCS). In particular, a pipeline for feeding a liquid under high pressure generally has a small internal diameter, between 2 and 3mm for example.

Known instantaneous flow-rate meters, such as turbine and Coriolis-type meters for example, have relatively large dimensions that are incompatible with the characteristic sizes of pipelines for feeding fluids under high pressure.

In particular, the mounting of known sensors on a high-pressure pipeline would require enlarging the diameter, which would introduce considerable perturbations in the dynamic flow of the liquid and lead to not very reliable measurement of the instantaneous flow rate.

Measurement of the flow rate of a fluid in a pipeline by means of a pressure sensor is also known of. It can in fact be demonstrated that, assuming specific assumptions to be satisfied, the flow rate of a fluid varies in function of the pressure measured at a single point inside the pipeline. In particular, the principle of these assumptions is that pressure pulsations pass through the fluid and travel in

single direction along the pipeline, for example, only towards the outlet, i.e. the sensor must not receive reflected pressure waves. It has been calculated that in the case of a diesel fuel injection circuit, this assumption holds true if the injector is connected to a tank via a discharge pipeline that has a length greater or equal to 11 metres and the pressure sensor is mounted immediately downstream of the same injector.

However, in this case, the liquid that flows in the discharge pipeline is at low pressure and, in addition, the dimensions of the discharge pipeline are incompatible with numerous applications.

To avoid these drawbacks, methods have been proposed that measure the instantaneous flow rate on the basis of measuring the speed of propagation of sound waves in the flowing liquid. For example, a device is known of that comprises an acoustic wave source and a plurality of pressure sensors placed downstream of the acoustic wave source.

However, it is important to note that the speed of the acoustic waves in a flowing liquid is given by the relation:

$$v = |u| \pm a \quad \text{where,}$$

'a' is the speed of sound in the liquid, and

'u' is the average speed of the liquid inside the pipeline.

Generally, the value of the speed of sound in high-pressure liquids is approximately 1000 m/s while the value of the liquid's average speed is less than 10 m/s. Thus, errors made in the evaluation of 'v' have heavy repercussions on the value of 'u'.

Another method for calculating the instantaneous flow rate of

a liquid in a high-pressure pipeline is that of modelling the hydraulic circuit by means of a numerical code. However, the numerical code requires accurate modelling of the mechanical, electronic and hydraulic components and therefore entails long configuration times.

DISCLOSURE OF INVENTION

The object of the present invention is to provide a method for determining the instantaneous flow rate of a fluid, in particular of a liquid under high pressure, devoid of the above-specified drawbacks.

The object of the present invention is embodied by means of a method according to claim 1.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention, a preferred embodiment is now described, purely by way of a non-limitative example, with reference to the enclosed drawings, where:

- Figure 1 is a diagram of a fuel injection circuit for a diesel engine able to embody the method according to the present invention, and
- Figures 2-4 are respective graphs that show the instantaneous flow rate values calculated (solid line) via a numerical code and the instantaneous flow rate values determined with the method of the present invention for different measuring conditions.

BEST MODE FOR CARRYING OUT THE INVENTION

In Figure 1, reference numeral 1 indicates a fuel injection circuit for a diesel engine comprising a rotary pump 2, a tubular element 3 connected to the pump 2 via a high-pressure pipeline 4, a plurality of injectors 5' and 5'' with the pilot stages connected in parallel with respect to the tubular

element 3 and a pressure relief valve 6 to connect the tubular element 3 with a tank (non shown) in order to limit the maximum pressure of the fuel inside the tubular element 3.

In particular, each injector 5' and 5'' is connected to the tubular element 3 by a respective high-pressure tube 8 having an internal diameter of 2.4 mm.

A device is also mounted in the fuel injection circuit 1 to measure the instantaneous flow rate under high pressure, comprising at least two pressure sensors 9 and 10 mounted at a distance 'l' on a straight section of at least one of the high-pressure pipes 8, for example on the pipeline connected to injector 5'', and a processing device 11 connected to the pressure sensors 9 and 10 to compensate and filter the signals coming from the sensors 9 and 10.

For example, the pressure sensors 9 and 10 are piezoresistive.

In particular, the processing device 11 implements commercial algorithms to compensate the signal coming from the pressure sensors 9 and 10 in order eliminate the signal's time drift. In addition, the signal is filtered to eliminate the effects of electrical interference on the pressure signals.

The processing device 11 also implements an equation that connects the instantaneous flow rate to the value of the linear pressure gradient measured via the sensors 9 and 10. This equation resolves a mathematical model based on a system of partial derivative equations including the mass conservation equation and the momentum balance equation.

The flow of a fluid under high pressure for engineering applications such as those previously mentioned satisfies the condition that the Mach number is low, and therefore the

previously mentioned system can be written as follows:

$$\begin{cases} \frac{\partial G}{\partial t} + \frac{\partial}{\partial x}(p + \rho u^2) \cdot A = -\pi \cdot d \cdot \tau_w \\ \frac{\partial G}{\partial x} + A \cdot \frac{\partial \rho^0}{\partial t} = 0 \end{cases} \quad (\text{sys. 1}) \text{ where}$$

't' is the time,

'x' is the position along the axis of the high-pressure pipeline 8,

'ρ' is the average density along the transverse section of the high-pressure pipeline 8,

'u' is the average speed of the liquid along the transverse section of the high-pressure pipeline 8,

'p' is the pressure of the liquid along the transverse section of the high-pressure pipeline 8,

'd' is the internal diameter of the high-pressure pipeline 8,

'G' is the mass flow of the liquid,

'A' is the area of the passage section of the high-pressure pipeline 8, and

'τ_w' is the wall friction.

According to a preferred embodiment, the wall friction is calculated via the following expression:

$$\tau_w = \frac{\lambda}{8\rho A^2} |G| G \text{ where}$$

'λ' is the coefficient of friction calculated according to the Darcy-Weisbach law.

According to a preferred embodiment, the system 1 can be resolved as follows to obtain a non-linear first-order total differential equation.

In particular, from the assumption that the Mach number is low, it follows that:

$$p^0 = p + \frac{1}{2} \rho u^2 \quad \text{where}$$

' p^0 ' is the absolute pressure of the liquid.

After the substitution of this relation in the momentum balance equation and a spatial integration with respect to positions x_9 and x_{10} of the pressure sensors 9 and 10, the system can be expressed as:

$$\begin{cases} \frac{d\bar{G}}{dt} + \frac{p_{10}^0 - p_9^0}{l} \cdot A + \frac{1}{2 \cdot l \cdot A} \cdot \left(\frac{G_{10}^2}{\rho_{10}^0} - \frac{G_9^2}{\rho_9^0} \right) = -\pi \cdot d \cdot \bar{\tau}_w & \text{where} \\ \frac{G_{10} - G_9}{l} = A \int_{x_9}^{x_{10}} \frac{\partial \rho^0}{\partial t} dx \end{cases}$$

$$\bar{\tau}_w = \frac{\lambda}{8 \bar{\rho} A^2} |\bar{G}| \bar{G} \quad \text{and} \quad \bar{G}(t) = \frac{1}{l} \int_{x_9}^{x_{10}} G dx \approx \frac{G_9 + G_{10}}{2}$$

It is also necessary to consider that the following approximations do not introduce a loss in accuracy when the temperature difference of the liquid between sensor 9 and sensor 10 is negligible, or rather less than 0.5°:

$$\frac{1}{l} \int_{x_9}^{x_{10}} \frac{\partial \rho^0}{\partial t} dx \approx \frac{1}{2} \cdot \left[\left(a_9^0 \right)^{-2} \cdot \frac{\partial p^0}{\partial t} \Big|_{x_9} + \left(a_{10}^0 \right)^{-2} \cdot \frac{\partial p^0}{\partial t} \Big|_{x_{10}} \right] \quad \text{and}$$

$$\begin{aligned} \rho_9^0 &\approx \rho_{10}^0 \approx \rho^0 \\ a_9^0 &\approx a_{10}^0 \approx a^0 \end{aligned} \quad \text{where}$$

' a^0 ' is the absolute sound velocity in isothermal conditions.

After having made the opportune substitutions, the model based on the system 1 reduces to the following equation:

$$\frac{d\bar{G}}{dt} + \frac{p_{10}^0 - p_9^0}{l} \cdot A + \frac{\bar{G}}{2 \cdot l \cdot A \cdot E^0} \cdot \left(\left. \frac{\partial p^0}{\partial t} \right|_{x_9} + \left. \frac{\partial p^0}{\partial t} \right|_{x_{10}} \right) = -\pi \cdot d \cdot \bar{\tau}_w \quad \text{where}$$

$E^0 = \rho^0 \cdot (a^0)^2$ is the isothermal elasticity modulus of the fluid.

The resolving equation can be subsequently discretized by a first-order explicit Euler numeric method to express the flow rate at instant 't_k':

$$\bar{G}_k = \bar{G}_0 + \Delta t \cdot \sum_{j=0}^{k-1} \left[\frac{p_{9,j}^0 - p_{10,j}^0}{l} \cdot A - \frac{\bar{G}_j}{2 \cdot l \cdot A \cdot E^0} \cdot \left(\frac{p_{9,j+1}^0 - p_{9,j}^0}{\Delta t} + \frac{p_{10,j+1}^0 - p_{10,j}^0}{\Delta t} \right) - \pi \cdot d \cdot \frac{\lambda}{8 \cdot \rho^0 \cdot A^2} \bar{G}_j \right]$$

(eq. 1) where

' $\bar{G}_0$ ' is the value of the flow rate at instant 't₀' when observation commences.

In particular, it is important to note that equation 1 depends on the pressure gradient along the axis of the pipeline 8, it being possible to enter the numeric values of all of the other quantities as average spatial values between the position of sensor 9 and that of sensor 10.

It is also important to note that it is preferable for parameter 'l' to be greater than a minimum value defined by the relation:

$$l_{\min} = 2a\Delta t \quad \text{where}$$

'a' is the speed of sound in the fluid, and

'Δt' is the sampling period of sensors 9 and 10.

For example, 'l' is between 2l_{min} and 4l_{min}, preferably around 3l_{min}.

Before measuring the pressure gradient, it is preferable to

set the zero of the two pressure sensors 9 and 10 to ensure that the difference in the measured pressures is null when the electrical signal coming from the pressure sensors 9 and 10 is the same.

In particular, downstream of the injector 5'', it is possible to mount a first flow meter 13 to measure the average flow rate in an injection cycle of fuel injected inside the combustion chamber and a second flow meter 14 to measure the average flow rate in an injection cycle recycled by the pilot stage of the injector. The sum ' G_m ' of these average flow rates in an injection cycle is measured for each injection cycle that, for example, starts at ' t_0 ' and finishes at ' t_f '. The sum ' G_m ' of the average flow rates for an injection cycle can also be calculated via equation 1 and therefore the following relation must always be satisfied:

$$\overline{G}_m = \frac{1}{f} \sum_{k=1}^f \overline{G}_k = G_m \quad (\text{eq. 2}) \quad \text{where}$$

'f' is the number of flow rate values calculated in an injection cycle and is an integer multiple of ' Δt '.

Furthermore, the flow rate at the start and at the end of each injection cycle must coincide, that is:

$$\overline{G}_0 = \overline{G}_f \quad (\text{eq. 3})$$

The calibration can thus be carried out or checked after purchase of the measurement device through the following phases:

- measuring the average flow ' G_m ' that runs through the pipeline 8 via means of measurement mounted downstream of the injector 5'',
- calculating the value of $\overline{G}_0$ via equation 2,
- calculating the value of $\overline{G}_f$ via equation 1, and

- checking equation 3.

Calibration terminates when equations 2 and 3 are simultaneously satisfied.

Figures 2, 3 and 4 show a comparison between the results of a numerical model 1D and the flow rate determined with the method of the present invention under different conditions of energization time of the injector 5'', pressure in the tubular element 3, injector holes and maximum injector lift, respectively 1000 μ s, 1000 bar, 0.3 mm and 7 holes (Figure 2), 1200 μ s, 1250 bar, 0.3 mm and 7 holes (Figure 3), and 550 μ s, 1400 bar, 0.43 mm and 6 holes (Figure 4).

In particular, the data determined via the present method is indicated with a circular symbol and the flow rate calculated via numerical modelling 1D, which is considered as the reference, is indicated by a solid line. As can be noted, the unison between experimental and theoretical data is extremely high, even when taking measurements in just two points of the high-pressure pipeline 8. It is therefore shown that the model used and the associated assumptions for obtaining equation 1 describe the basic phenomena of non-steady flow of a fluid in a pipeline.

The advantages that can be achieved with the method according to the present invention are the following.

Two pressure sensors allow the linear pressure gradient to be calculated and the combination with the model including the mass conservation equation and the momentum balance equation allows very good results to be achieved in a simple manner for determining the instantaneous flow rate in a pipeline, in particular even in a pipeline inside which particularly intense pressure wave propagation phenomena occur, such as

those caused by the reflection of the same waves in correspondence to the injector of an injection circuit for example.

The spatial integration phase of the system 1 allows a total derivatives system to be obtained and a consequent simplification of the model, which can thus be resolved even by a simple and inexpensive analogue circuit.

The particular formulation of equation 1 highlights parameter 'l', which allows the relative position of the sensors 9 and 10 to be defined in simple manner to improve the precision of measurement.

The calibration method allows the measurement device to be regulated in a simple manner to obtain precise measurement of the linear pressure gradient.

Finally, it is clear that modifications and variants can be made to the method described and illustrated herein without leaving the scope of protection of the present invention, as defined in the enclosed claims.

Equation 1 requires the modulus of elasticity and the density of the fluid to be determined for calculating the wall friction. These properties weakly depend on pressure and temperature. It is therefore possible to provide, for the purpose of further increasing the precision in determining the instantaneous flow rate, an additional sensor to detect the absolute pressure and the temperature of the liquid.

Furthermore, the pressure sensors 9 and 10 could also both be piezoelectric to further improve measurement precision of the pressure gradient.

When the sensors 9 and 10 are piezoelectric, the optional third sensor can be piezoresistive to measure both the absolute pressure and the average temperature.

The sensors 9 and 10 can also be different from each other, for example, a piezoelectric sensor and a piezoresistive sensor, so as to be able to simultaneously measure the absolute pressure as well as the pressure gradient and the average temperature.

CLAIMS

1. Method for determining the instantaneous flow rate of a fluid in a pipeline (8) comprising the phases of:

- measuring the pressure gradient of the fluid by detecting the pressure in at least two points (X_9 and X_{10}) of said pipeline (8), longitudinally set apart at a certain distance (1),
- determining the instantaneous flow rate using the value of said pressure gradient in a model based on a system of differential equations including the mass conservation equation and the momentum balance equation.

2. Method according to claim 1, characterized in that said phase of measuring the pressure difference comprises the phase of using means of measurement comprising a first and a second pressure sensor (9 and 10), at least said first sensor (9 or 10) being a piezoelectric sensor or a piezoresistive sensor.

3. Method according to claim 2, characterized in that it also comprises the phase of measuring at least the absolute pressure of the fluid.

4. Method according to any of the previous claims, characterized in that said system of differential equations is expressed in the form:

$$\begin{cases} \frac{\partial G}{\partial t} + \frac{\partial}{\partial x}(p + \rho u^2) \cdot A = -\pi \cdot d \cdot \tau_w \\ \frac{\partial G}{\partial x} + A \cdot \frac{\partial \rho^0}{\partial t} = 0 \end{cases}$$

where,

't' is the time,

'x' is the position along the axis of said pipeline (8),

'p' is the average density of the fluid along a transverse section of said pipeline (8),

'u' is the average speed of the fluid along a transverse section of said pipeline (8),
 'p' is the pressure of the fluid along the transverse section of the said pipeline (8),
 'd' is the internal diameter of the said pipeline (8),
 'G' is the mass flow of the fluid,
 'A' is the area of the passage section of said pipeline (8),
 and
 ' τ_w ' is the wall friction.

5. Method according to claim 4, characterized in that said model is also based on the following expression:

$$p^0 = p + \frac{1}{2} \rho u^2$$

6. Method according to one of claims 4 or 5, characterized in that said model is obtained via the spatial integration of said system of equations to obtain a system of total derivative equations with respect to time and for making said distance (1) explicit.

7. Method according to claim 6, characterized in that said distance (1) is between $2l_{\min}$ and $4l_{\min}$, where:

$$l_{\min} = 2a\Delta t \quad \text{where}$$

'a' is the speed of sound in the fluid, and

' Δt ' is the pressure-measurement sampling period.

8. Method according to any of the previous claims, characterized in that said model is defined by the following equation:

$$\frac{d\bar{G}}{dt} + \frac{p_{10}^0 - p_9^0}{l} \cdot A + \frac{\bar{G}}{2 \cdot l \cdot A \cdot E^0} \cdot \left(\left. \frac{\partial p^0}{\partial t} \right|_{x_9} + \left. \frac{\partial p^0}{\partial t} \right|_{x_{10}} \right) = -\pi \cdot d \cdot \bar{\tau}_w \quad \text{where}$$

the subscripts 9 and 10 refer to values determined in said at least two points.

9. Calibration method for a measurement device comprising at least two pressure sensors (9 and 10) and embodying the method according to any of the previous claims, characterized in that it comprises the following phases:

- performing a variable flow cycle such that the initial flow and the final flow rates are equal,
- measuring the average flow rate G_m that passes through said pipeline (8) during said cycle by means of flow rate measurement (13 and 14),
- applying the method according to any of the previous claims to determine the average flow rate of the cycle $\overline{G}_m$, the initial flow rate $\overline{G}_0$ and the final flow rate $\overline{G}_f$, and
- modifying the calibration of said sensors until the following relations are simultaneously satisfied:

$$\overline{G}_m = G_m \quad \text{and} \quad \overline{G}_f = \overline{G}_0.$$

FIG. 2

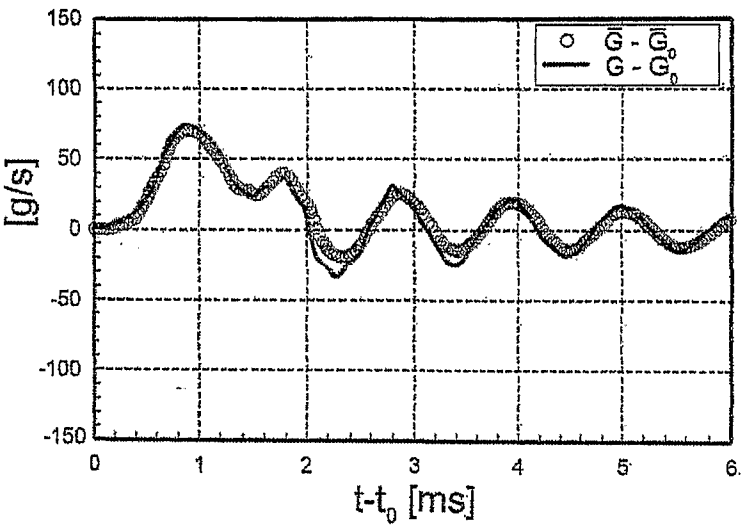


FIG. 3

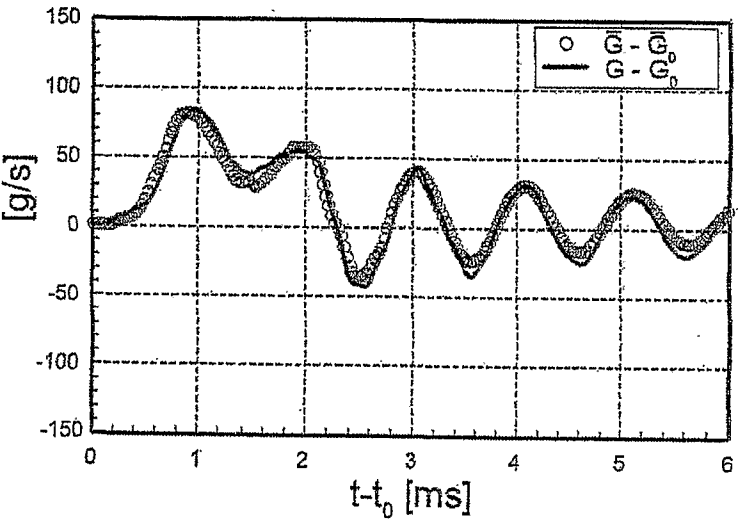


FIG. 4

