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A Novel Simple Technique for Measuring the Volumetric Flow Rate and Direction of Flow Inside a Pipe – The Single and Double Coils Sensors

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ABSTRACT

This work shows how a single coil wrapped on a pipe can be used to measure the volumetric flow rate inside the pipe and how by wrapping a second coil the flow direction can be detected. The developed method is very simple, accurate, and cover all the range of flow from low speed to high speed with more accuracy expected at high speed. Few turns are sufficient for the coils, no calibration is needed, and the method can be used for all kinds of fluids even without the need to know the type of fluid inside the pipe. The principle of the developed method is theoretically explained and proved and then experimentally validated.

Keywords: volumetric flow rate sensor, flow direction detection, high speed velocity measurement. single coil sensor, double coils sensor.

INTRODUCTION

Flow rate measurement devices/sensors are essential in process industry and automatic control. Many techniques for measuring the volumetric flow rates are exist [1-7]. Even with the variety of this existing techniques, no single technique can cover all the needs for flow measurements. Every technique has a certain applications/ specification needs to be considered for selecting the proper technique for specific applications. The developed method in the present work adds a new technique with many great advantages for the variety of flow measurement techniques.

Obstruction free flowmeters like ultrasonic and magnetic flow meters gain a great research and industrial interest in the last decades. Today ultrasonic and magnetic flowmeters are widely used in the industry because their great advantages over other flowmeters [8-11]. These two techniques are competitive to the developed technique in this work. Table 1 shows a comparison of these two techniques with the new developed sensor in this work.

The new developed sensor in this work shall be called "single coil sensor" if one coil is used and "double coils sensor" if two coils are used. The single coil sensor is used when only the volumetric flow rate is to be measured and the double coils sensor is used when both volumetric flow rate and direction of flow are to be known.

In this paper, first, the developed single coil sensor is introduced, and the principle of operation is explained and proved. Second, the double coil sensor is introduced and how the direction of flow can be found by adding a second coil is explained. Third, the design of the sensor is considered. Fourth, the operation of the developed sensor is validated experimentally. Finally, conclusions about the developed concept are drawn.

METHODS

Flow measurement (The single coil sensor)

Consider a coil wrapped on a pipe as shown in Figure 1. If the coil is supplied by a constant

Table 1. Comparison between the ultrasonic and magnetic flowmeters with the new developed sensor

Technique	Principle of operation	Type of fluid
Ultrasonic	Doppler shift	Sonically reflective fluids: slurries, liquids with bubbles, gases with particles, turbulent flow, blood flow [12].
Ultrasonic	Time of flight	Only extremely clean liquids or gases [13]
Ultrasonic	Doppler shift + time of flight	Combination of the above two types [14]
Magnetic/electromagnetics	Faraday's law of electromagnetic induction	Conductive fluids (only fluids with conductivity greater than 10 μS/cm) [13]
Magnetic/electromagnetics	Lorentz force	Conductive fluids [15, 16]
Magnetic/electromagnetics	Electromagnetic phase-shift	Conductive fluids [17]
This work (Magnetic/electromagnetics + energy conservation)	Magnetic convection (new developed concept)	All types of fluids: liquids, gasses, multiphase, liquid slurries, gas with particles, etc.

current source, then the volumetric flow rate inside the pipe is linearly proportional to the voltage generated across the current source (or coil). Therefore, by measuring the voltage across the current source the volumetric flow rate inside the pipe can be calculated. This fact can be proved simply by making energy balance on the coil as follow:

$$\begin{Bmatrix} \text{Energy Supplied by} \\ \text{the Current Source} \end{Bmatrix} = \begin{Bmatrix} \text{Energy Losses Due to the Resistance} \\ \text{of the Wire Wrapped on} \\ \text{the Coil (Ohmic Losses)} \end{Bmatrix} + \begin{Bmatrix} \text{Time Rate Change of Potential Energy} \\ \text{of the Magnetic Field Inside the Coil} \end{Bmatrix}$$

or mathematically,

$$I_s V_s = I_s^2 R_w + \frac{dW_m}{dt} \quad (1)$$

The potential energy of a magnetic field is [18]:

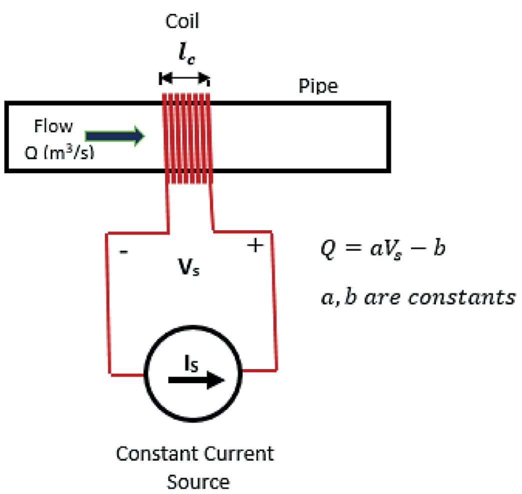

Figure 1. The single coil sensor

$$W_m = \frac{1}{2}\int \mu H^2 dv \quad (2)$$

Therefore, equation 1 becomes:

$$I_s V_s = I_s^2 R_w + \frac{d}{dt}\left[\frac{1}{2}\int \mu H^2 dv\right] \quad (3)$$

Using Leibniz rule, equation 3 becomes:

$$I_s V_s = I_s^2 R_w + \frac{1}{2}\mu H^2 \frac{dv}{dt} \quad (4)$$

The time derivative of the volume inside the coil (v) is the volumetric flow rate. i.e.

$$\frac{dv}{dt} = Q \quad (5)$$

Therefore, equation 4 becomes:

$$I_s V_s = I_s^2 R_w + \frac{1}{2}\mu H^2 Q \quad (6)$$

Equation 6 is the general equation for flow inside a coil. It relates the current inside the coil and the voltage across the coil with the volumetric flow rate inside the coil/pipe. The term $\frac{1}{2}\mu H^2 Q$ represent the amount of magnetic energy convicted by the flow (hence introducing the magnetic convection concept). Furthermore, for an ideal coil the magnetic field intensity H is [18]:

$$H = I_s \frac{N}{l_c} = I_s n \quad (7)$$

So, equation 6 becomes:

$$I_s V_s = I_s^2 R_w + \frac{1}{2}\mu_f (I_s n)^2 Q \quad (8)$$

or

$$V_s = I_s R_w + I_s \frac{1}{2}\mu_f n^2 Q \quad (9)$$

After rearrangement, equation 9 can be written as

$$Q = \frac{2}{\mu_f n^2}\left[\frac{V_s}{I_s} - R_w\right] \quad (10)$$

or

$$Q = aV_s - b \quad (11)$$

where:

$$a = \frac{2}{I_s \mu_f n^2} \text{ and } b = \frac{2}{\mu_f n^2} R_w \quad (12)$$

Are constants for constant current source. Therefore, equation 11 completes the proof. The flow can be measured by measuring the voltage across the current source and then use equation 10 to calculate the volumetric flow rate. Moreover equation 9 can be written as

$$V_s = I_s R_w + I_s R_f = I_s (R_w + R_f) \quad (13)$$

where:

$$R_f = \frac{1}{2}\mu_f n^2 Q \quad (14)$$

is the flow resistance. Therefore, the constant current source sees two resistances, the wire resistance and the flow resistance. If the flow rate is zero then R_f is zero and the constant current source sees only the wire resistance. Figure 2 shows the equivalent circuit of the sensor.

An equivalent alternative technique can be made by applying a constant voltage source across the coil instead of constant current source and measuring the current generated in the coil then use equation 10 to calculate the volumetric flow rate. This alternative technique results in an inverse relationship between the volumetric flow rate and the current ($Q \propto \frac{1}{I_s}$). Direct relationship is usually more favored over inverse relationship. For this reason, we will limit this research to constant current supply.

Direction detection (The double coil sensor)

The energy balance equation can be interpreted in different way. For example, equation 8 can be interpreted as:

$$\underbrace{I_s V_s}_{\substack{\text{Energy Suplied}\\ \text{by the Source}}} = \underbrace{I_s^2 R_w}_{\substack{\text{Energy Disspated}\\ \text{in the Wire}}} + \underbrace{\frac{1}{2}\mu_f (I_s n)^2 Q}_{\substack{\text{Convection of Magnatic}\\ \text{Energy by the Flow}}}$$

Therefore, the energy term $\frac{1}{2}\mu (I_s n)^2 Q$ is convicted by the flow and some of it can be retrieved back by adding a second coil downstream of the flow. The second coil will pick up some of this energy by induction. Figure 3 shows the double coil sensor. To calculate the energy transmitted to the second coil, again we make energy balance on the second coil as follow:

(*Convicted magnetic energy from the first coil by the flow*)·*k* = = *Energy induced in the second coil*

or

$$\frac{1}{2}\mu_f (I_s n)^2 Q\, k = I_2^2 (R_2 + R_{w2}) \quad (15)$$

The left-hand side of equation 15 is multiplied by a fraction k $(0 \leq k \leq 1)$ because not necessarily all the convicted energy can be absorbed by the second coil. The constant k can be interpreted as the coupling coefficient between the two coils due to the convection of magnetic energy from the first coil to the second coil by the flow. The idea here is the same as in the transformer, but the two coils are coupled by the flow instead of ferromagnetic metal as in the transformer. The value of k can be determined experimentally but for the purpose of flow direction detection, the value of k is not needed as will be explained shortly. In the double coil sensor, the flow measurement coil shall be called the primary coil and the direction detection coil shell be called the secondary coil. Rearranging equation 15 to get

$$I_2 = \sqrt{\frac{\mu_f (I_s n)^2 Q\, k}{2.(R_2 + R_{w2})}} \tag{16}$$

Therefore, the voltage drop across R_2 is

$$V_{R_2} = R_2 \sqrt{\frac{\mu_f (I_s n)^2 Q\, k}{2.(R_2 + R_{w2})}} = \tag{17}$$
$$= I_s n R_2 \sqrt{\frac{\mu_f Q\, k}{2.(R_2 + R_{w2})}}$$

Now we can explain how the second coil can detect the flow direction as follow:

1. If the flow is from left to wright: The fluid picks magnetic energy from the primary coil and when it passes through the secondary coil it induce a non-zero voltage drop across R_2 (Equation 17). The polarity is not important (though it can be determined from Lenz's law).
2. If the flow is from wright to left: No voltage drop created across R_2 since the fluid coming from the wright holds no magnetic energy.

In other words, the voltage drop across R_2 is measured. If the reading is non-zero, then the flow is from left to wright. If the reading is zero, then the flow is from wright to left. An alternative approach can be made by putting a very sensitive light bulb instead of R_2. If the bulb is ON, then the flow is from left to wright. If the bulb is OFF, then the flow is from wright to left.

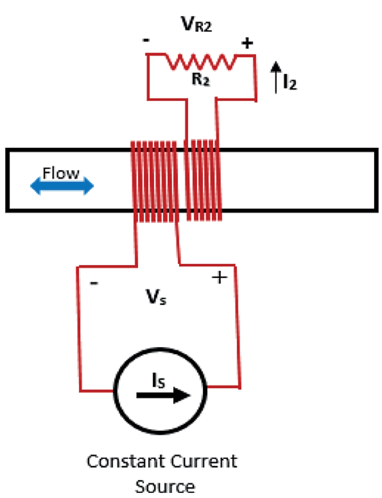

Figure 3. The double coil sensor: Flow rate measurement and direction detection

SENSOR DESIGN CONSIDERATIONS

Sensor sensitivity

To enhance the sensitivity of the developed sensor, the sensor should be designed such that R_f / R_w is maximized. The following new dimensionless number can be defined:

$$r = \frac{R_f}{R_w} = \tag{19}$$
$$= \frac{Flow\ Resistance}{Coil\ Wire\ Resistance} = \frac{\frac{1}{2}\left[\frac{\mu_f N}{l_c}\right]^2 Q}{\frac{l_w}{\sigma . A_w}}$$

Assuming single layer coil (one layer is usually sufficient for the purpose of this sensor), then $l_w = N.\pi.D_p$, $l_c = N.D_w$ and $A_w = \frac{\pi}{4} D_w^2$

Therefore, the ratio becomes

$$r = \frac{\frac{1}{2}\left[\frac{\mu_f N}{N.D_w}\right]^2 Q}{\frac{N.\pi.D_p}{\sigma . A_w}} = \frac{1}{8}\frac{{\mu_f}^2 \sigma}{N.D_p} Q \tag{20}$$

Therefore, to maximize r the following points must be considered:

- N should be selected as minimum as possible $(r \propto \frac{1}{N})$. The minimum is one, but one turn requires a precision instrument/circuit to measure Vs. Therefore, N should be selected as minimum as possible but must be high enough to be compatible with the sensitivity of the instrument/circuit used to measure Vs.
- The sensor is more suitable for small diameter pipes $(r \propto \frac{1}{D_P})$.
- Copper wire should be selected for the coil $(r \propto \sigma)$.
- The sensor is expected to be more accurate at high flow rates $(r \propto Q)$.

Magnetic permeability

Referring to equation 10 it can be noticed that, to use this equation, the magnetic permeability of the fluid must be known (which is the only property needs to be known). Unfortunately, this property is available for few fluids in the literature (water, air, oxygen and hydrogen). Table 2 lists the relative permeability of these fluids. It seems that if other type of fluid to be used its magnetic permeability must be measured, but fortunately, this is not the case. The reason can be explained as follow.

The magnetic permeability of nonmagnetic fluids/materials are very close to one [18]. Therefore, by introducing a very small error to equation 10, it can be assumed that the permeability of all kinds of fluids (excluding magnetic fluids or fluids that contain magnetic particles) is the same as the permeability of vacuum ($4\pi \times 10^{-7}$ H/m). So, equation 10 becomes:

$$Q = \frac{1}{2\pi x 10^{-7} n^2}\left[\frac{V_s}{I_s} - R_w\right] \tag{21}$$

Which is applicable for all kinds of fluids. Now the permeability is not needed, and therefore, the sensor can be used even without the need to know the type of fluid inside the pipe. However, this idea remains a suggestion, if not convinced enough then equation 10 can be applied.

Sensor advantages

The new sensor has the following advantages:
- Very simple and can be directly installed on the pipe (clamp-on) by wrapping a few turns of copper wire on the pipe. The sensor can also be made ready-to-use (in-line) and commercialized.
- The sensor can be used for any type of nonmagnetic fluid even without the need to know the type of fluid inside the pipe if the assumption to be used.
- The sensor covers all the range of flows from low speed to very high speed (including supersonic and hypersonic flows without any upper limit). Moreover, the sensor is expected to be more accurate at high speed.
- The sensor is bidirectional, and the direction of flow can be easily detected.
- The sensor is temperature, pressure, and composition totally independent.
- Very accurate (error less than 3%) and no calibration is needed. The theory behind the sensor which is developed based on the energy balance (first law of thermodynamics) and the well-founded low in electromagnetics (potential energy of a magnetic field, W_m) is sufficient to trust the sensor. In addition, the sensor was experimentally validated.
- The sensor can be used for any type of pipe material (metal or nonmetal). Since we are using constant current source, the magnetic field inside the pipe wall is constant, and therefore, the time derivative of this field is zero. Hence, the material of the pipe does not matter.

EXPERIMENTAL VALIDATION OF THE SENSOR

Experimental setup

The developed method was tested using the equipment shown in Figure 4. A distilled water was used in the testing. The volumetric flow rate was controlled by hand valve and measured by rotameter. The double coils sensor was built by wrapping a copper wires of gauge 25 AWG (Diameter = 0.4547 mm) on a 1-inch pipe of schedule 80 (OD = 33.4 mm, ID = 24.3 mm) made of vinyl. The direction of the flow in the pipe was reversed by flipping the ends of the pipe. A constant current source of 0.5A was applied across the primary coil and the generated voltages was measured using a precision micro voltmeters. The volumetric flow rate was covered from 0 to 45 mL/min. The specifications of the equipment/devices used in the testing are shown in Table 3.

Procedure of measurements

The objective of the experimental setup was to measure the volumetric flow rates by the sensor and compare it with the rotameter readings. The procedure for measuring the flow rates is as follow:
- The required flow rate was set by the hand valve and the rotameter reading was taken.

Table 2. Relative magnetic permeability of some fluids [18]. The permeability of free space is $4\pi \times 10^{-7}$ H/m

Fluid	μ_r
Water	0.9999912
Air	1.00000037
Oxygen	0.999998
Hydrogen	1
Vacuum	1

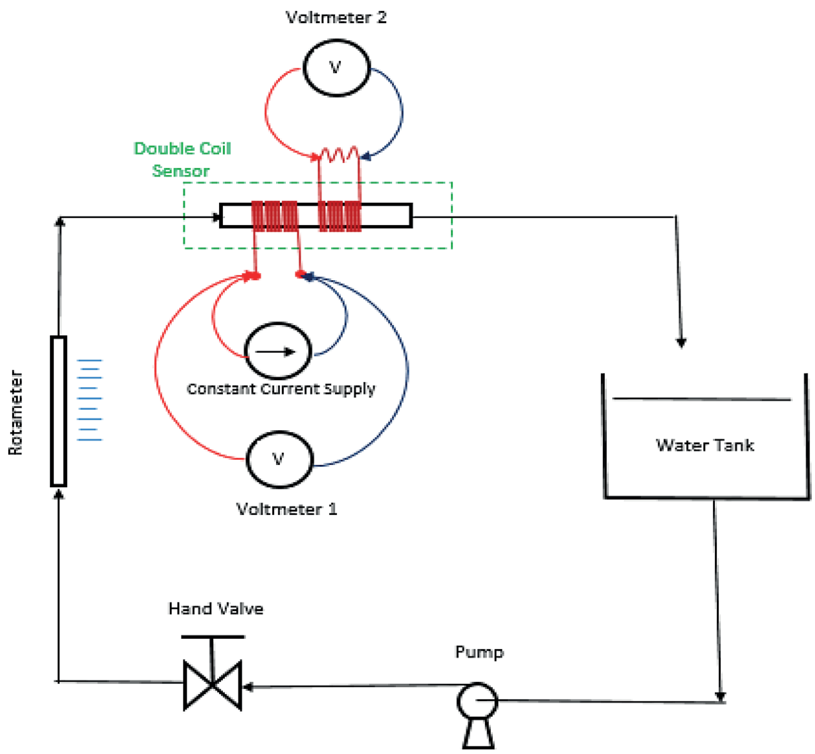

Figure 4. Schematic representation of the equipment used to test the sensor

- The voltage drop across the primary coil was read using voltmeter 1 and equation 10 was used to calculate the volumetric flow rate. This is the sensor reading.

And the procedure for detecting flow direction is as follow:

- The direction of flow is set from left to wright and the reading of voltmeter 2 was taken and recorded as a function of flow rate.
- The direction of flow was reversed by flipping the ends of the pipe and again the reading of voltmeter 2 was taken and recorded as a function of flow rate.

The error in the measured values of the sensor was calculated from equation 10 as follow:

$$\frac{\Delta Q}{Q} = \sqrt{\left(2\frac{\Delta l_c}{l_c}\right)^2 + \left(2\frac{\Delta N}{N}\right)^2 + \left(\frac{\Delta V_s}{V_s}\right)^2 + \left(\frac{\Delta I_s}{I_s}\right)^2 + \left(\frac{\Delta R_w}{R_w}\right)^2} \quad (18)$$

RESULTS

Figure 5 shows the experimental results obtained by plotting the calculated volumetric flow rates from the measured value of V_s (eq. 10) in

Table 3. Specifications of the used equipment/devices in the testing

Equipment/device	Type	Accuracy
Rotameter	Nxtop	± 1 L/min
Constant power supply	HANMATEK	0.001 A
Voltmeters 1 and 2	Edulab micro voltmeter	± 0.5 μV
Rw	Wire resistance	± 0.001 ohm
R2	Wire resistance	± 0.001 ohm
Pipe diameter	1 inch schedule 80	± 0.05 mm
Wire diameter	25 AWG (diameter = 0.4547 mm)	± 0.0001 mm
Wire lengths	1.574 m Copper	± 0.001 mm
N1	15 Turn	± 0.25 (approximation)
N2	15 Turn	± 0.25 (approximation)

comparison with the direct measured values of the rotameter readings. The error bar calculated from equation 18 also included in the plot. From Figure 5, the following points can be noticed:

- The voltage generated across the coil does depends on the volumetric flow rate and the relationship is linear as theoretically proved previous.
- The calculated and measured values are in excellent agreement. All the measured values are lying within the uncertainty bar of the sensor. The R^2 of the measured values by the sensor is $R^2 = 0.97$.

Figure 6 shows the experimental results of the direction detection coil. From the figure, the following points can be noticed:

- For flows from wright to left: no voltages crated across R^2 regardless of the volumetric flow rate.
- For flows from left to wright a small voltage drop (in μV) was crated on R_2. This voltage drop increase with increasing volumetric flow rate ($V_{R2} \propto \sqrt{Q}$) which is in agreement with equation 17.

The above two notes validate the operation of the direction detection coil. As mentioned before, the value of k is not needed. However, its value for water still can be determined from the above experimental data by plotting $V_{R2} \propto \sqrt{Q}$. Figure 7 shows this plot.

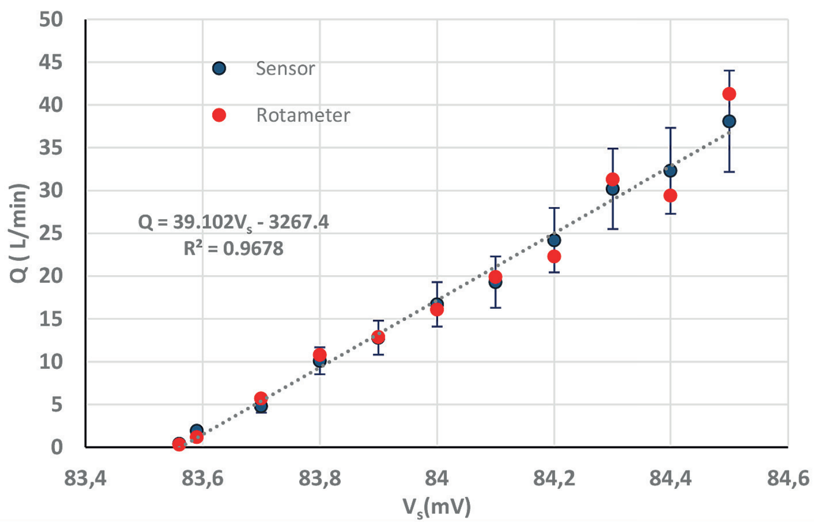

Figure 5. Comparison of the sensor measurements and the rotameter readings

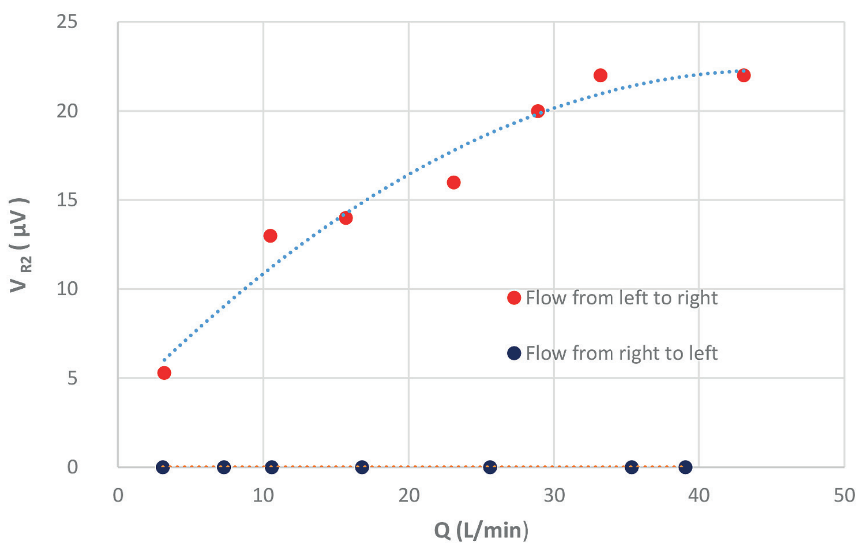

Figure 6. Voltage drop generated across the secondary coil

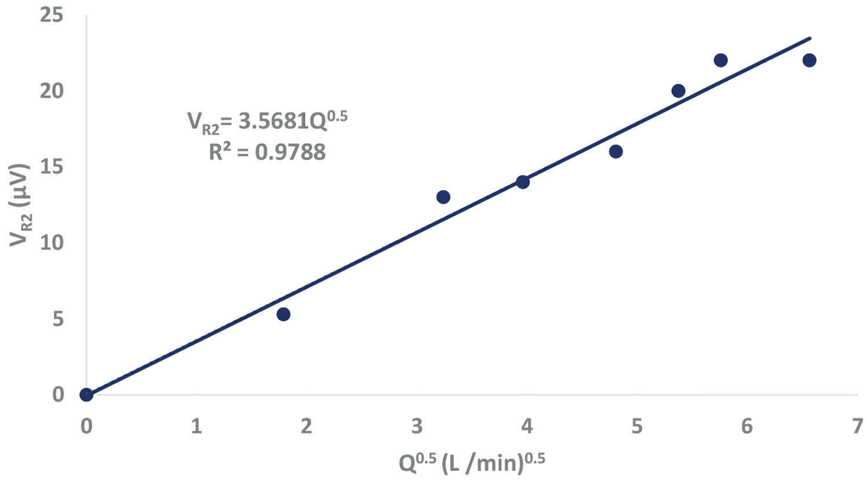

Figure 7. Linear regression to find the value of k for water

From equation 17 the slope is $I_s n R_2 \sqrt{\frac{\mu_f\, k}{2.(R_2 + R_{w2})}}$ from which the value of k can be obtained. By doing this it was found that for water k = 12.25 ×10^{-6}. This means that the energy induced in the secondary coil over the magnetic energy taken from the first coil and carried out by the flow is about 12 ppm. This is a very small value but still expected for nonmagnetic materials like water.

CONCLUSIONS

Magnetic energy can be convicted by flow, this energy is equal to $1/2\mu H^2 \cdot Q$. Therefore, every fluid in motion pass through a magnetic field absorb and convict some of magnetic energy taken from this field. Moreover, some of this convicted magnetic energy can be retrieved back by passing the fluid through a coil. These new physical concepts are important and can be of great value in future works for understanding some natural phenomena and developing new ideas.

REFERENCES

1. Miller R.W. Flow Measurement Engineering Handbook. McGraw Hill, 1996.
2. LaNasa P.J. and Upp E.L. Fluid Flow Measurement: A Practical Guide to Accurate Flow Measurement. Butterworth Heinemann, 2014.
3. Smith C.A. and Corripio A.B. Principles and Practice of Automatic Process Control. Willy, 2015.
4. Endress and Hauser Company Documentations: Flow Measuring Technology for Liquids, Gases and a Steam, https://www.endress.com/en/downloads, 3/2018.

Nomenclature

I – current, A	μ – magnetic permeability, henry/m
V – voltage, V	v – volume, m^3
W – potential energy, J	l – length, m
R – resistance, ohm	k – coupling coefficient, –
H – magnetic field intensity, A/m	σ – electric conductivity, Siemens/m
Q – volumetric flow rate, m^3/s	s – source
A – area, m^2	m – magnetic
D – diameter, m	w – wire
n – number of turns	c – coil
t – time, s	f – fluid

5. https://www.siemens.com/global/en.html.
6. https://www.omega.com/en-us/resources/flow-meters.
7. https://www.flowmeters.com.
8. Lynnworth L.C. and Y Liu, Ultrasonic flowmeters: Half-century Progress Report, Ultrasonic, 2006, Volume 44, Pages e1371-e1378.
9. Li K. and Colm S., Electromagnetic Flow Meters Achieve High Accuracy in Industrial Applications, Analog Dialogue, 2014, canada.newark.com.
10. Sanderson M.L., Electronics and Power, Electromagnetic and ultrasonic flowmeters: Their Present States and Future Possibilities. 1982, ieeexplore.ieee.org.
11. Corte S., Choose the Right Flowmeter, Chemical Engineering. Vol. 108, Issue 1, 2001.
12. Deok-Woo P., Shang-Yoon H., Chungyong K. and Gyu-Sik K., A Study on an Ultrasonic Flow Meter. International Journal of Innovative Science, Engineering & Technology, Vol. 4 Issue 8, 2017.
13. Deepa K., Industrial Flow Meters/Flow Transmitters, Texas Instruments Documentation, 2012.
14. Hironobu Y. et.al, Advanced Hybrid Type Ultrasonic Flow Meter Utilizing State-of-the-Art Pulsed-Doppler Method Along With Traditional Transit Time Method, 4th International Symposium on Ultrasonic Doppler Method for Fluid Mechanics and Fluid Engineering, 2004.
15. Janis P., Dominique B., Gunter G.. Contactless Electromagnetic Phase-Shift Flowmeter for Liquid Metals. Measurement Science and Technology, 2011, 22(5):055402.
16. Richard L. and Jānis P. Concept of a Next-Generation Electromagnetic Phase-Shift Flowmeter for Liquid Metals. Flow Measurement and Instrumentation, Volume 65, 2019, Pages 128-135.
17. Andr´e T., Evgeny V., Bernard K., and Oleg Z. Theory of the Lorentz Force Flowmeter, New Journal of Physics, 2007.
18. Sadiku M. Elements of Electromagnetics. Oxford University Press, 2014.