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Ultrasonic Thermal Energy Measurement System

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Abstract – A solution for measuring the thermal energy based on an ultrasonic flowmeter and a resistance temperature detector is presented in this paper. The electronic module was build around a dedicated time to digital converter integrated circuit. Due to the TDC-GP2 implemented functionality, including precision temperature measurement, fire pulse generation, windowing and clock calibration it was sufficient to add a low power microprocessor MSP430 and a transducer dependant driver and receiver. A software aplication implements the SPI comunication, measurement cycle, data processing and the user interface

Keywords: ultrasonic flowmeter, heatmeter, resistance temperature detector, time to digital converter, SPI interface

I. INTRODUCTION

The measurement of thermal energy flow is based on the measurement of two physical properties: flow rate and temperature difference. The analogy with the measurement of electrical energy is significant. The electrical energy [Wh] consumed in a resistance is calculated from the potential difference [V] measured between the resistance terminals, and the flow of electrons, current [A]. The equivalent to consumed thermal energy is calculated from the temperature difference between point C and D [degree C] and the flow of water[m^3/s].

The measurement of thermal energy is in principle similar to electrical energy, however due to the physical differences, like dimension of water pipes, complexity of installations it is more difficult in practice than electrical energy measurement. The accuracy of the measurements depends not only on the sensors and instruments used but also on the correct place where the sensors are positioned.

There are different types of parameters that have to be measured for calculating the quantity of heat produced:

- the flow rate V [m3/s]
- the in / out temperature: t_F [K] / t_R [K]
- the time t [s]

These parameters allow the calculation of heat power

$$P: P = \rho * c_p * V * (t_F - t_R) \text{ [kW]}$$

The density ρ [kg/m3³] and the specific heat capacity c_p [J/(kg*K)]depend on the type and temperature of the fluid used (and if the fluid is a gas also on the pressure). Knowing the power, it is possible to calculate the quantity of heat energy Q [kJ]:Q = P * t

II. PARAMETERS MEASUREMENT

Heat counters, from the smallest domestic appliances to the largest industrial equipment, consist of three basic components:

1. A flow meter for measuring the water flow- water is used almost exclusively as heat transfer medium
2. Temperature sensors - to measure the temperature difference
3. An integrator for calculate the energy

Various principles to measure the flow rate exist. The most prominent flowmeters are: electromagnetic flowmeter (used for conductive liquid), ultrasonic flowmeter, vortex flowmeter and flowmeter with rotating impeller

A. *Principle of the ultrasonic flowmeter:*

Within the Transit Time Principle the measurement is made by sending bursts of signals through a pipe. The measurement of flow is based on the principle that sound waves travelling in the direction of the fluid flow require less time than when travelling in the opposite direction. The difference in transit times of the ultrasonic signals is an indication for the flow rate of the fluid. The transit time method is ilustrated in Figure 1.

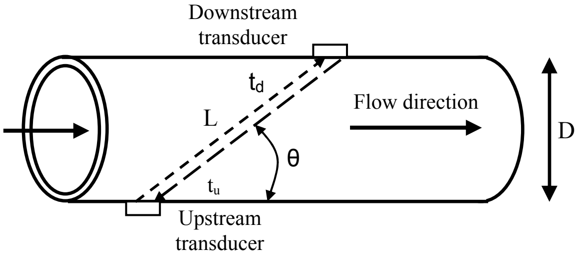

Fig.1. The transit time ultrasonic flowmeter setup

The time for acoustic waves to travel from the upstream transducer to the downstream transducer t_d is shorter than the time required for the same waves to travel from downstream to the upstream t_u. This times t_d and t_u can be expressed in the following forms:

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$$t_d = \frac{L}{c + v\cos\theta}; \quad t_u = \frac{L}{c - v\cos\theta}, \qquad (1)$$

where c is the sound speed in the fluid, v is the flow velocity, L is the distance between the transducers and θ is the angle between the flow direction and the line formed by the transducers.

The difference of t_d and t_u is

$$\Delta t = t_u - t_d = \frac{L}{c - v\cdot\cos\theta} - \frac{L}{c + v\cdot\cos\theta}$$
$$= \frac{2\cdot v\cdot L\cdot\cos\theta}{c^2 - v^2\cdot\cos^2\theta} = \frac{\frac{2\cdot v\cdot X}{c^2}}{1-(v/c)^2\cdot\cos^2\theta} \qquad (2)$$

where X is the projected length of the path along the pipe direction (X = L cosθ). To simplify, we assume that the flow velocity v is much smaller than the sound speed c, that is, $v << c \Rightarrow (v/c)^2 \cong 0 << 1$

We then have $\Delta t \cong \frac{2\cdot v\cdot x}{c^2}$ or $v \cong \frac{\Delta t\cdot c^2}{2\cdot x}$ (3)

Since ultrasonic signals can also penetrate solid materials, the transducers can be mounted onto the outside of the pipe. Fast Digital Signal Processors and signal analysis guarantee reliable measuring results even under difficult conditions where previously ultrasonic flowmeters have failed.

Doppler ultrasonic flowmeters operate on the Doppler shift principle, whereby the transmitted frequency is altered linearly by being reflected from particles and bubbles in the fluid. The net result is a frequency shift between transmitter and receiver frequencies that can be directly related to the flow velocity. If the pipe internal diameter is known, the volumetric flow rate can be calculated. Doppler meters require a minimum amount of solid particles or air in the line to achieve accurate measurements.

B. Temperature sensors

Sensors and instruments are available on the market that perform the same measurement but vary significantly in accuracy and precision. To measure temperatures in a flow of water, usually thermocouples or platinum resistance (PT-) sensors are used. Thermocouple sensors are available for different temperature ranges each with its own accuracy. A PT temperature sensor can have a higher precision than a thermocouple.

Resistance temperature detector

A Resistance Temperature Detector (RTD) is a temperature responsive device based on a predictable resistance change in the sensing element. The EN 60751 standard specifies requirements for industrial Platinum resistance sensors and covers the PT 100 thermometers.

The most important advantages of RTDs are: high accuracy, excellent long-term stability, high signal output level which allows transmission over long distances without ancillary equipment.

Thermocouple thermometer

A thermocouple (TC) consists of two wires of different conductive material, connected each other by means of two junctions forming an electrical circuit. If one junction is at temperature T1 and the other at T2, then an electromotive force is generated in the circuit and it depends on the materials and temperatures T1 and T2 (Seebeck effect). In an industrial TC thermometer one junction is the measuring joint, and the other is a reference one which is usually located in correspondence with the conversion electronics .

C. The integrator

With the flow rate and temperature sensors, the parameters are measured. It is now necessary to calculate the thermal power and the thermal energy with a calculator/processor, using (temperature dependent) values of density and specific heat capacity of the circulating fluid.

The quantity of thermal energy transferred from the heating water to the heat consumer over a defined period of time is proportional to the temperature difference between the flow and return and to the volume of heating water that has flowed through.

The heating water volume and the difference in temperature between the flow and return are multiplied and its product integrated.

The energy supplied in the system can be calculated as follows.

$$E = \int_0^t P(t)\times dt = \int_0^t K(T_F)\times Q_F \times (T_F - T_R)\times dt \qquad (4)$$

where

P(t) = Power as function of the time

$K(T_F)$ = K factor - including ρ and c_p dependence

Q_F = Flowrate forward

T_F = Temperature forward

T_R = Temperature return

Every hour accumulated heat and water quantities as well as hour counter are stored in a permanent memory. All the data will be stored in the event of a power failure.

III. ULTRASONIC HEATMETER ARHITECTURE

An ultrasonic heatmeter consist of the following parts:

- a calibrated measuring way, which contains two ultrasonic transducers;
- the RTD sensors for offset compensation and measuring input and output temperature in heat-metering arrangement;
- the electronic module;

Regarding the electronic part, the main aim in implementing a transit time ultrasonic heatmeter was to obtain a low power, low cost solution. Following this aim a dedicated time to digital converter TDC-GP2 controlled by a low power microcontroller MSP430F449 from Texas Instruments was used.

The TDC-GP2 is perfectly suited for low-cost ultrasonic heatmeter designs. Due to the implemented functionality, including precision temperature measurement, fire pulse generation, windowing and clock calibration it is sufficient to add a simple microprocessor (without A/D converter) and a transducer dependant driver and receiver. The extremely low current consumption guarantees the necessary long battery lifetime in such applications.

The measurement is fairly automated by the TDC-GP2. The microprocessor just sends a start command. The TDC then fires the transducers and measures the time of flight. It calibrates the results and provides them to the microprocessor.

The block diagram of such a system is presented in figure 2. Around the core of the electronic module consisting of TDC-GP2 and MSP430 processor, a few number of components are necessary for interfacing ultrasonic transducers, the LCD display and to implement the data change in a hierarchical network. In order to eliminate the errors associated with the software trigger of measurement, in the transducer interface is hardware generated the START signal for TDC-unit from the emitted signal. The interface was designed also to realize the switching of the received signal in accordance to the measurement configuration.

The LCD display controlled by the LCD controller integrated into MSP430 implements the user interface.

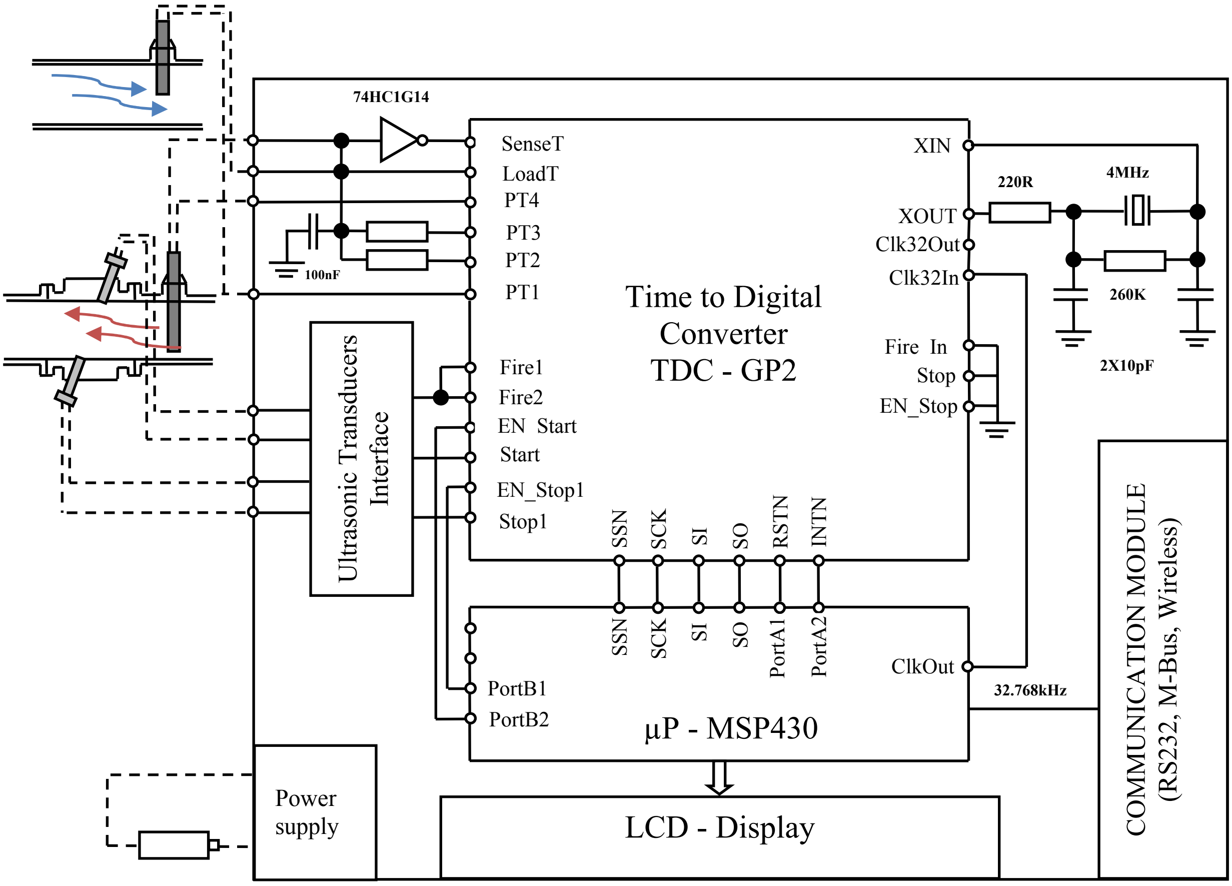

Fig. 2. The block diagram of an Ultrasonic Heatmeter

IV. TIME TO DIGITAL CONVERTER

TDC-GP2 is the next generation of ACAM GmbH general purpose TDCs. Higher resolution and smaller package size make it ideal for cost sensitive industrial applications.With special functional blocks like a fire-pulse generator, stop-enable, temperature measurement, and clock control it is perfectly suited for ultrasonic flow-meter and heat-meter applications – Figure 3. Digital TDCs use internal propagation delays of signals through gates to measure time intervals with very high precision. Figure 4 clarifies the principal structure of such an absolute-time TDC. Intelligent circuit structures, redundant circuitry and special methods of layout on the chip make it possible to reconstruct the exact number of gates passed by the signal. The maximum possible resolution strongly depends on the maximum possible gate propagation delay on the chip.

The measuring unit is actuated by a START signal and stopped by a STOP signal. Based on the position of the ring oscillator and the coarse counter the time interval between START and STOP is calculated with a 20 Bit measurement range.

In measurement range 2 the maximum time interval is extended using a pre-divider. The resolution in LSB remains unchanged. In this mode the high speed unit of the TDC does not measure the whole time interval but only time intervals from START and STOP to the next rising edge of the reference clock (fine-counts).

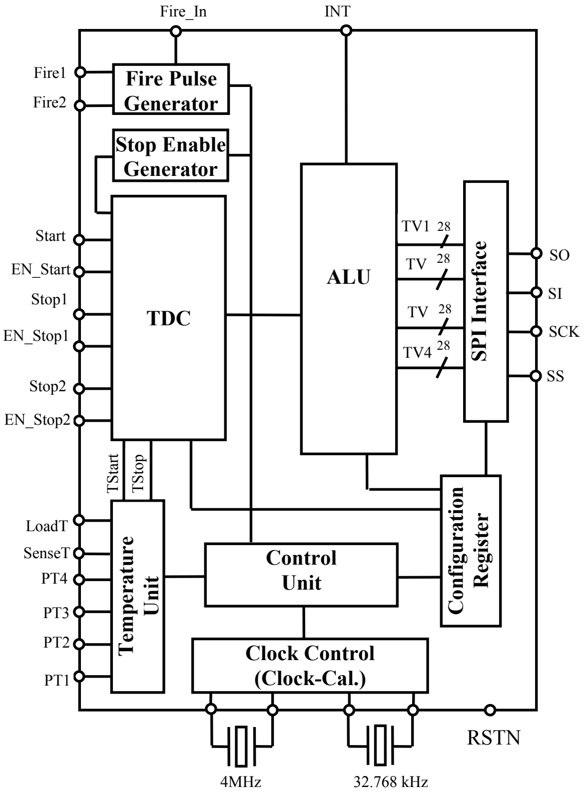

Fig. 3. TDC-GP2 – Structure

Between the fine-counts the TDC counts the number of periods of the reference clock (coarse-count). The gate propagation delay times strongly depend on temperature and voltage. In measuring range 2 the result is the sum of different fine and coarse-count results. Therefore in measuring range 2it is necessary to make a calibration. During a calibration the TDC measures 1 and 2 periods of the reference clock. The measurement range is limited by size of the coarse counter: tyy = Tref x 214 ≈ 4 ms @ 4MHz. The time interval between START and STOP is calculated with a 26 Bit measurement range.

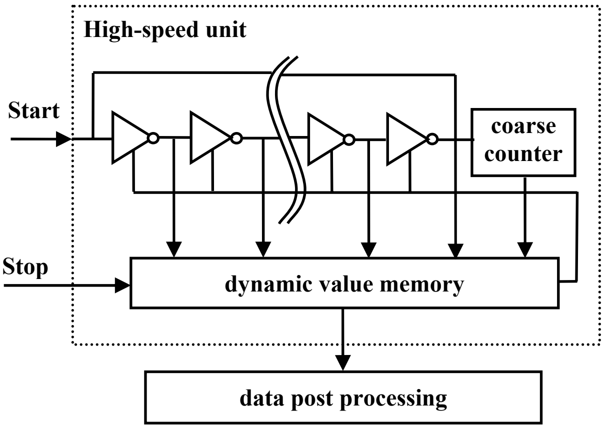

Fig. 4 TDC – measuring unit

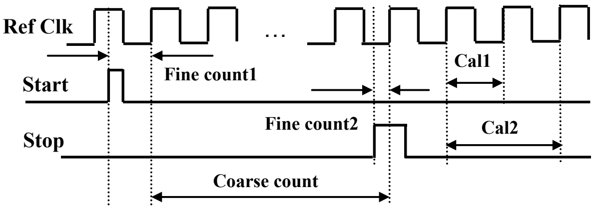

Fig. 5 TDC – time diagram

A. *Fire-pulse Generator*

The fire-pulse generator generates a sequence of pulses which is highly programmable in frequency, phase and number of pulses. The high-speed oscillator frequency divided by the factor selected for ClkHSDiv is used as the basic frequency. This frequency is internally doubled and can freely be divided by a factor of 2 to 15. It is possible to generate 1 to 15 pulses. For each pulse the phase can be adjusted per register configuration. The fire-pulse generator is activated by sending opcode Start_Cycle. The fire-pulse generator provides 2 outputs, Fire1 and Fire2. The driver strength of each output is 48mA @5V. These two outputs can be paralleled to increase the driver strength up to 96 mA. Furthermore, each output signal can be inverted to double the signal amplitude. The outputs can be set individually to high-Z. The fire- pulse generator allows to generate and send pulse sequences multiple times for use in a quasi “sing around” method. Using this feature the received pulse sequence is fed into TDC-GP2 Fire_In input. It is digitally amplified and directly forwarded to the output buffer for an immediate re-emittance without any clock delay.

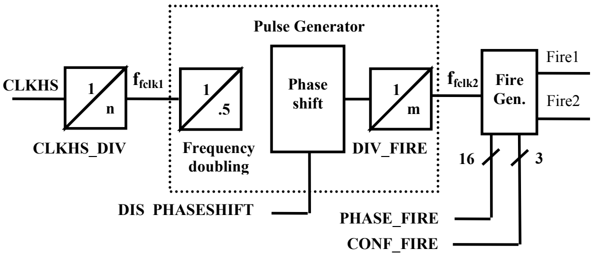

Fig. 6 The Fire Pulse Generator

The TDC-GP2 offers a Phase-Noise function that decouples the calibration clock from the fire pulse generator. Therefore to the fire pulse phase is continuously added noise and shifted against the internal reference clock. This is necessary to provide the necessary statistics for averaging. The phasenoise function does not decrease the accuracy of the result.

B. *Temperature Measurement*

Especially for heat meter applications the TDC-GP2 has a temperature measuring unit that offers high resolution and very low current consumption. The measurement is based on measuring discharge times. A capacitor is discharged alternately through the sense resistors and the reference resistors. The unit has four resistor ports with the following function:

PT1 reference resistor lower temperature
PT2 sense resistor lower temperature

PT3 sense resistor lower temperature
PT4 reference resistor higher temperature

The temperature sensor should have a minimum resistance of 500 Ohm. The TDC-GP2 measures the discharge times of the RC-networks made of each resistor and the capacitor – see figure 7.

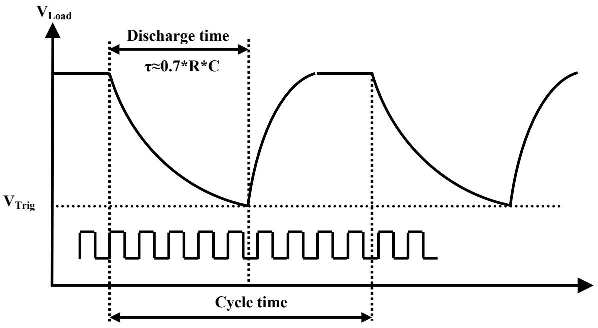

Fig. 7 The temperature measurement cycle

The precision of the temperature measurement is about 0.004°C, several times better than needed for heat meters. The temperature measurement is fully automated. It is triggered by the µC sending the opcode "Start_Temp". The TDC-GP2 controls the four measurements by itself. After the four measurements have finished the interrupt flag is set. The four data are found in registers 0 to 3.

From RES_2/RES_1 and RES_3/RES_4 the microcontroller can calculate the ratio Rtemp/Rref. By means of a look-up table it can calculate the temperature for the special type of sensor in use.

C. *SPI-interface*

The configuration of TDC is made by the microcontroler through a serial interface compatible with the 4-wire SPI standard:SSN - Slave Select, SCK - SPI Clock, SI - SPI Data In, SO - SPI Data Out

The TDC-GP2 does only support the following SPI mode: Clock Phase Bit =, Clock Polarity Bit =0

It is mandatory to set the SSN – line to Highstate for at least 50ns between each Read-/Write sequence.

The SerialSelectNot (SSN) line is the HIGH-active reset for the serial interface. After SSN is set to LOW different operations can be addressed, not depending on the status of the interface before the reset.

The transfer starts with the MSB and is finished sending the LSB. After sending the last Bit TDC-GP2 transfers the data into the target register or executes the command. It is not possible to do incremental writing. Each register must be addressed separately. When reading from the chip it is necessary to send the opcode first, too. With the first positive edge of the clock following the opcode, the TDC-GP2 sends the MSB of the addressed register to SO output. Each positive edge transfers the next lower bit to the output. Table 1 sumarizes the SPI operational codes by which the microcontroler initializes and configures the TDC (Init, Write to ADR, Reset), start time and temperature measurements (Start_Cycle, Start_Temp) and reads the results or the status register (Read from ADR)

Table 1

8 Bit OP Code								
MSB							LSB	Description
1	0	0	0	0	ADR2	ADR1	ADR0	Write to ADR
1	0	1	1	0	ADR2	ADR1	ADR0	Read from ADR
0	1	1	1	0	0	0	0	Init
0	1	0	1	0	0	0	0	Power on Reset
0	0	0	0	0	0	0	1	Start_Cycle
0	0	0	0	0	0	1	0	Start_Temp
0	0	0	0	0	0	1	1	Start_Cal_ Resonator
0	0	0	0	0	1	0	0	Start_Cal_TDC

V. EXPERIMENTAL RESULTS

The heatmeter was made up of the following parts:

- a calibrated measuring way, which contains two ultrasonic transducers and two ultrasound reflector, by means of which the ultrasonic signal is transmitted between the two transducers – figure 8;
- two temperature sensors for offset compensation and heating evaluation in a dedicated heat-metering arrangement;
- an electronic module supplied by a 6V battery;

For a measuring way length of 8 cm, with a ultrasound velocity of c = 1450 m/s and a fluid velocity of v = 0,01 m/s, the measured time difference only amounts to Δt = 0.76 nanoseconds. With the transit-time method, the time measurement must be taken in hundred picoseconds in order for the smaller flow velocities to be resolved with the required accuracy. The 45^0 reflector's based measuring configuration maximizes the signal level due to the fact that the propagation of the ultrasonic wave is on the flow direction.

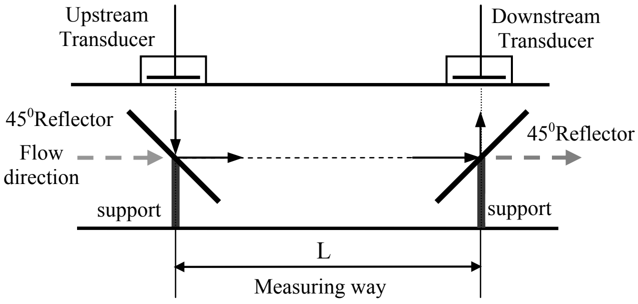

Fig.8 The measuring configuration setup

The software application running an MSP was developped using IAR Embedded Workbench to solve the folowing tasks:

- implementing the SPI protocol for MSP to TDC communication through a SPI interface
- TDC registers configuration and reading measurements results from TDC

- driving of the measurement cycle
- different parameters calculations based on the transit-time value and temperature measurements results received from TDC
- user interface through LCD display and keyboard
- flow rate calculation as a frequency output

Based on the transit time value and measuring way parameters a dedicated routine running on MSP is used to synthesize a pulsed signal output with the frequency proportional to the measured flow value.

The design was tested for values of flow between 10 l/h and 200 l/h at two different temperatures 30 °C and 60 °C. The flow range was swept from small to great values and back. The results presented in Fig. 9 and Fig. 10 show a temperature dependent offset. Among the causes of offset appearance are the temperature dependence of sound propagation and the dilatation of measurement path. The compensation was done using a look-up table with a number of predetermined values for different temperatures. Following a linear compensation, a range of errors between +-10 % was obtained for values of flow greater than 1 l/minut.

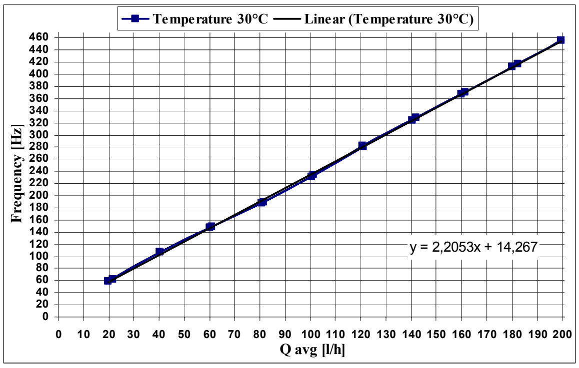

Fig.9. The frequency – flow dependence at 30°C

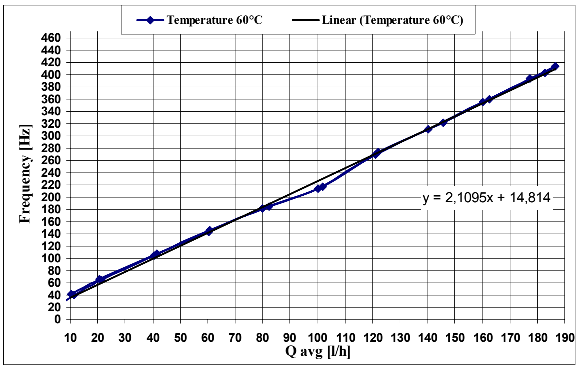

Fig.10. The frequency – flow dependence at 60°C

VI. CONCLUSION

The measurement principles of the thermal energy are presented based on the measurement of two physical properties: flow rate and temperature difference. The implented solution is based on a transit - time ultrasonic flowmeter and a resistance temperature detector. Using the above principle, a prototype model, based on low power dedicated components - TDC-GP2 and a MSP430 microcontroller - was then built and tested. It was found that the system operated as expected especially at low values of flow. The results confirms that the ultrasonic heatmeter has achieved the design objective. Further refinements to hardware and software for improving the accuracy and reliability of temperature and flow measurements are to be identificated.

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