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THERMAL ENERGY METER

Fast response test method for complete meter and subassembly

03/2024

Summary

Introduction:

Thermal energy meters are widely used in domestic and industrial applications where heat management involves production, conveying, storage and use. In these processes, accurate measure of thermal energy is a necessary condition to approach strategy for implementation of efficient method for costs reduction and environmental conservation.
Technical standards and metrological traceability infrastructure to national measurement standards define tests and calibrations procedures in permanent conditions. Operating conditions rarely meet permanent or near permanent regime, normally energy demand is characterised by significant variability over time.
Last revision of European norm EN1434:2022-4 define test method for fast response meters.
According to 7.4.2.4 fast response is a property of flow sensor only. This because main part of dynamic behaviour of thermal energy meter is due to flow sensor response.
More, we usually refer to continuous operating mode as for mechanical flow sensor but, for battery powered meters, also sampling rate pay a role in not permanent measuring conditions.
It's necessary to point out that during operation the flow sensor is exposed to environmental condition, is in contact to thermal energy conveying liquid and is subject to temperature stress cycle and many other influences that may affect measure accuracy and durability. Flow sensor is directly subject to measure suddenly variation of flow. Temperature sensors, due to great thermal inertia of conveying systems, is supposed to be less exposed to rapid variation of temperature.
An accurate analysis of complete meter reveal that measurement chain comprises also temperature sensors and calculator and these components may pay a role in dynamic response of whole meter.
Temperature sensors are mechanically robust, and dynamically characterized according to temperature sensor response time method in EN60751:2008, 6.5.2.
Even if the main parts of thermal energy meter are covered by EN1434, complete meter and calculator are missing.
This study intends to reduce this gap on complete meter by.

1) Analize complete thermal energy meter measuring chain to define parameter to be investigated.
2) Define test method.
3) Data processing.
4) Laboratory application.

All thermal energy meter has a user interface with a display and (in most cases) an energy pulse output. These devices are used in first and subsequent verification. The purpose of point 2) and 3) is to use information that are available by the meter (totalized energy and/or pulse energy output) to get dynamic parameters.

Complete thermal energy meter measuring chain.

Figure 1 show thermal energy meter where temperature sensors (forward and return) and flow sensor are connected to calculator.

Temperatures (forward and return) and flow rate can change during time independently. Calculator, according to input quantities compute energy during time and display total amount of energy.

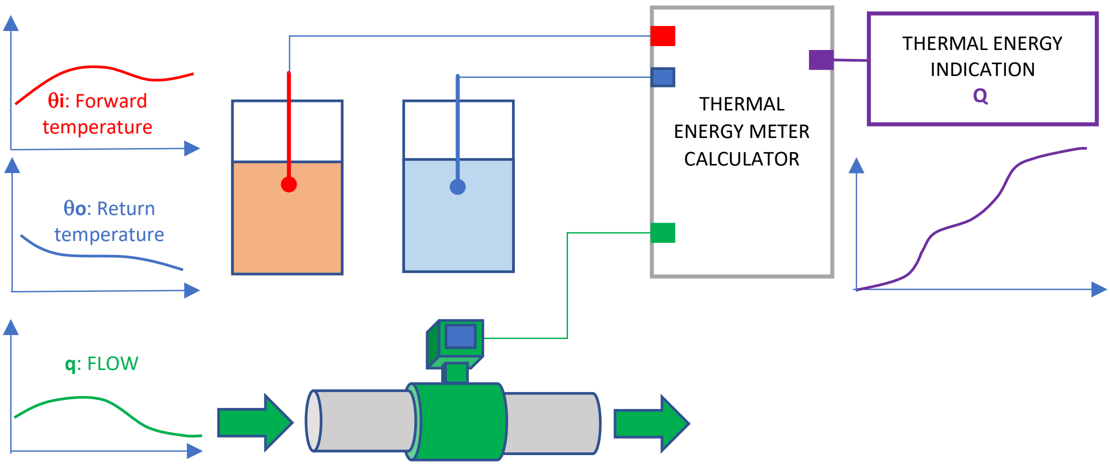

Figure 1

Considering $\Delta\theta(t) = \theta i(t) - \theta o(t) \geq 0$ and $q(t) \geq 0$ follow that energy indication $Q(t) \geq 0$ is a continuous non decreasing function of time.

Next equation reproduces measurement chain sketch of Figure 1:

$$Q = \int_{\Delta t} k_{Vo}(\theta_i - \theta_o)\, q\, dt$$

Equation 1

where:

Q Energy (J)

k_{Vo} heat coefficient (J/dm^3/K)

θ_i Inlet temperature – forward, (°C)

θ_o Output temperature – return, (°C)

q conveying liquid volume flow (dm^3/s)

Calculator is equipped with display as indicating device and usually also have an energy pulse output signal.

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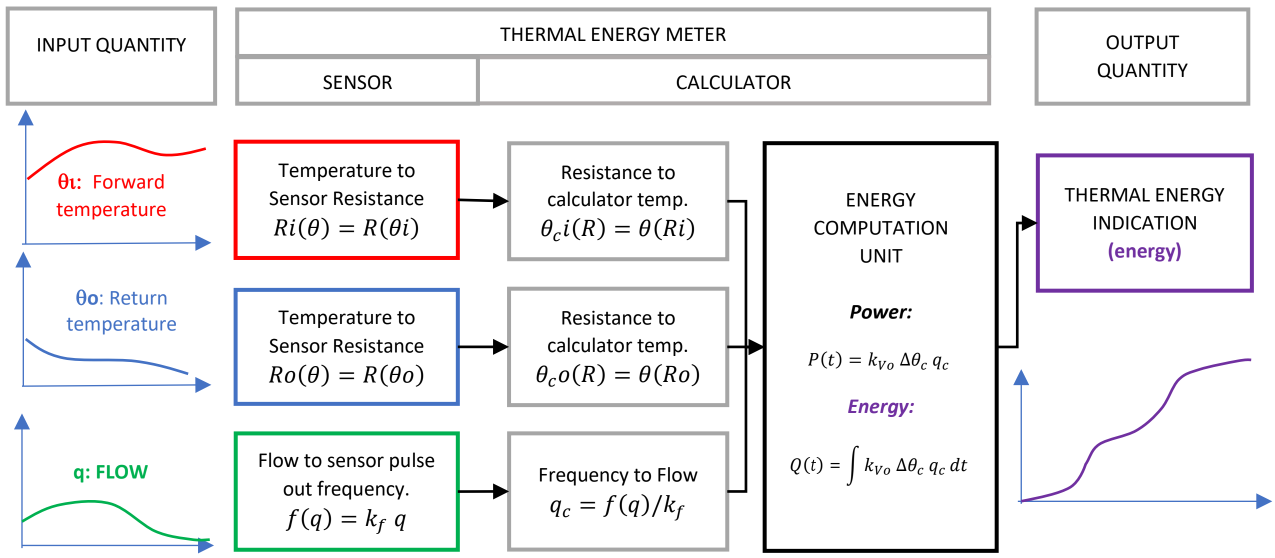
Next picture shows the block diagram of quantities and signal of physical layer of measurement chain:



Where:
$R(\theta) = R_0(1 + A\theta + B\theta^2)$: PT resistance according to EN 60751:2008 [Ω]
$\Delta\theta_c = \theta_c i - \theta_c o$: calculator measured temperature difference [K]
k_f: linear factor [Hz/(dm³/s)]

Figure 2

The metrological chain of Figure 2 show quantities that are involved in energy measurement assuming that each part is considered one to one function disregarding dynamic effect of each block.

To be clear, in Figure 2 we mean that temperature probe is capable to immediately reach the thermodynamic equilibrium to conveying fluid. Also, we mean that mechanical moving parts of flow sensor (eg. Impeller) have no inertia. To complete the chain, the calculator is capable to perform immediately energy computation without time delay and without dynamic behaviour on each measuring channel ($\theta_c i$, $\theta_c o$, q_c).

The metrological chain of Figure 2 is a good model for calibration and metrological verification of energy meter because dynamic properties have no effects due to required permanent calibration condition.

To investigate dynamic properties is necessary to “enlarge” permanent calibration model to dynamic model of the meter.

Figure 3 shows the same block diagram of metrological chain of Figure 2 where are included dynamic properties in each block. First order differential equation describes dynamic model of each block. This hypothesis is not completely justified because preclude more complex model that may better fit the actual dynamic behaviour of thermal energy meter. The main purpose is not to find the best dynamic model that fit accurately the actual dynamic property of the meter. The purpose is to consider a model as simple as possible that can represent both permanent conditions and dynamic condition also.

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The simpler model is described by first order differential equation.

In each block $G(s) = \frac{1}{\tau s+1}$ represent the transfer function in complex domain as ratio of output versus input. Each transfer function shows the unknown dynamic parameter τ (s) that characterizes dynamic behaviour.

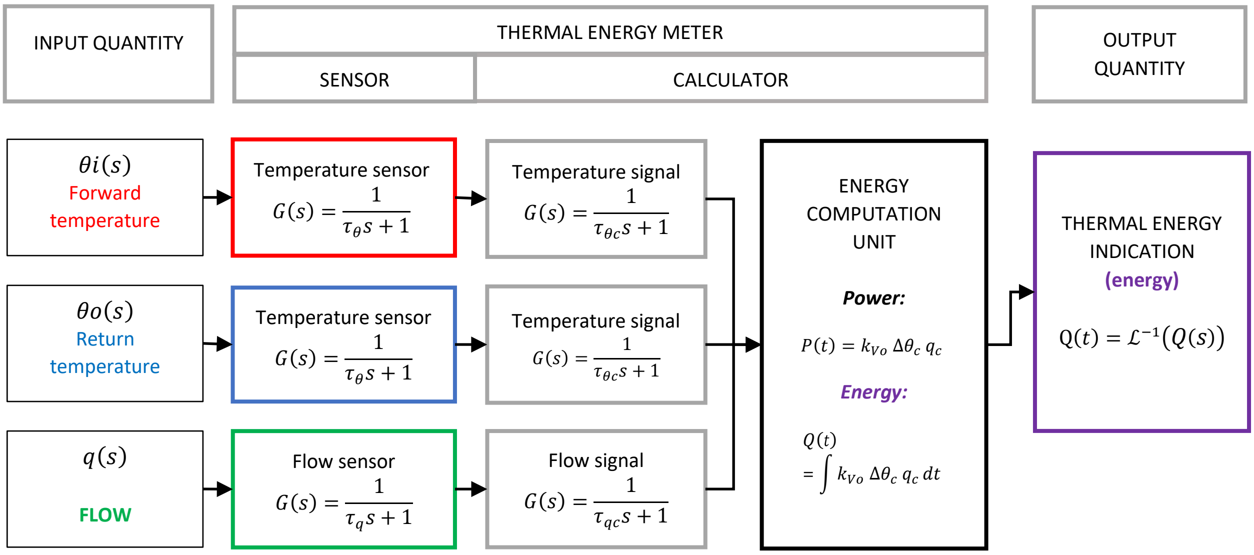


Figure 3

Figure 3 show that sensors (temperature and flow) and calculator contribute to dynamic behaviour of complete measuring chain. Is possible to test single component performing test on each block. As example is possible to test temperature sensor probes and calculator separately. This approach complies sub assembly dynamic characterization. For complete meter we can test at same time all measurement chain adopting a simplified block diagram of Figure 4.

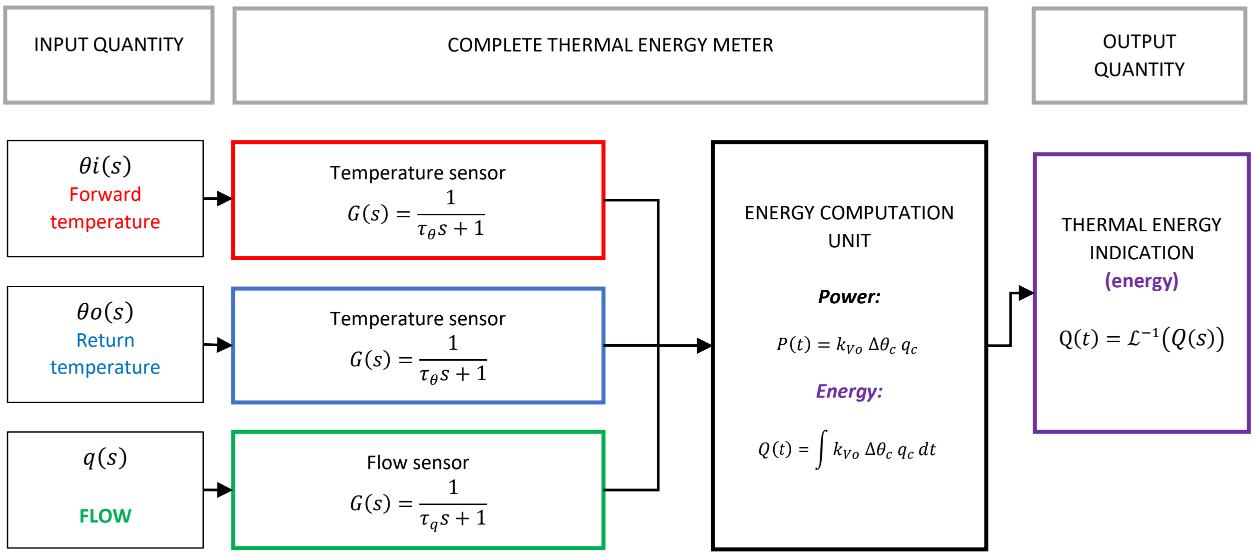


Figure 4

For complete meter we cannot test single subassembly separately, is necessary to test at same time all measurement chain, adopting a simplified block diagram of Figure 4. In this picture, unknown dynamic parameter τ (s) represent whole dynamic behaviour of each branch of measuring chain. In this way parameter τ (s) in Figure 4 represent a sort of "merge of effects" of sensor and calculator. (eg. $\tau = \tau_{\theta}$"+"$\tau_{\theta c}$).

Next part of present document focuses on test method that can be used.

TEST METHODS FOR COMPLETE METER

Is possible to test complete meter considering thermal power (P, [kW]) or energy counted (Q, [J]) as output quantity. Input quantities are:

- Temperature
- Flow

Test method consist in changing only one input maintaining permanent values for other one. In this way is possible to set two tests:

- Temperature step test (flow constant over time)
- Flow step test (temperatures constant over time)

In next part a complete analysis of methods is explained.

TEMPERATURE STEP RESPONSE

Is possible to obtain dynamic behaviour information considering output energy indication (or energy power) when subjected to an input step temperature.

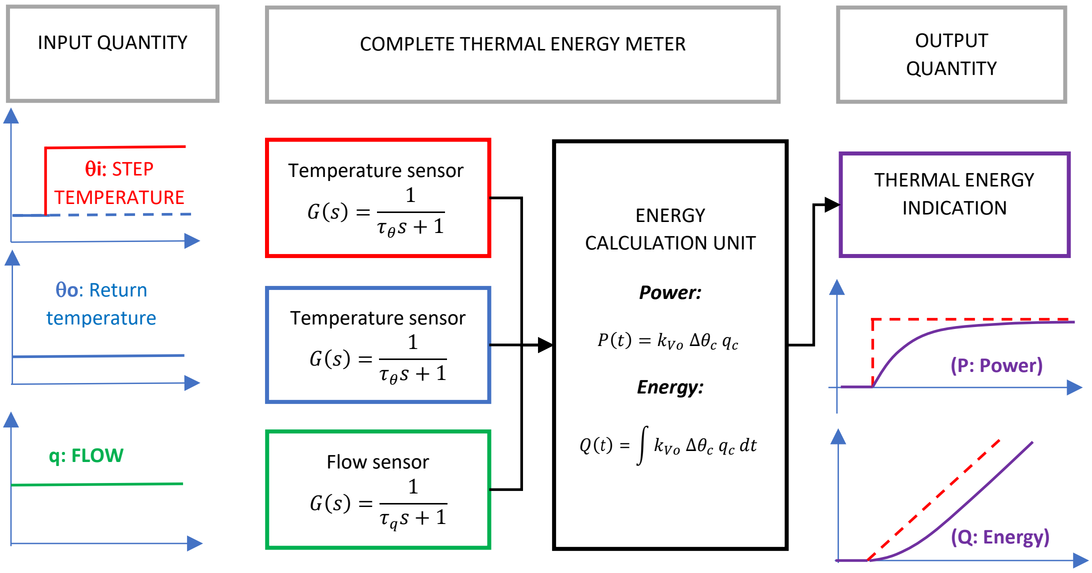


Figure 5

The output registration of energy totalizer, over the time, gives the possibility to evaluate the meter response when a temperature step is applied in input.

Test method:

Test facility is composed by two thermostatic baths. Each bath is set to a specific temperature to simulate a step when one of two the probes is moved from one to the other.

Before to generate the temperature step, both temperature sensors are posed in one of two baths (e.g. lower temperature) to get the equilibrium where $\Delta\theta(t) = \theta i(t) - \theta o(t) = 0$ is meet.

While the sensor is subjected to a constant flow rate[1] one of the two sensor is rapidly moved to the second bath.

During this operation a data logger (internal or external) register the energy totalizer during the time.

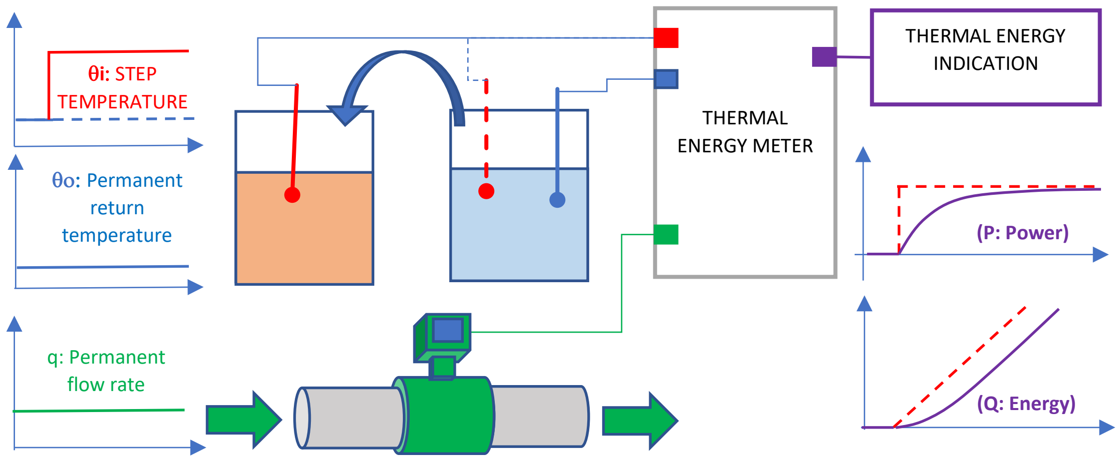


Figure 6

A data set of collected couple of values: time and Energy (t,Q(t)) is available for dynamic properties evaluation.

[1] Flow sensor signal can be simulated for sub assembly test when flow sensor is missing.

FLOW STEP RESPONSE

In analogy to previous temperature step test is possible to obtain information about meter dynamic behaviour based on output energy indication (or power) when subjected to an input step of flow rate.

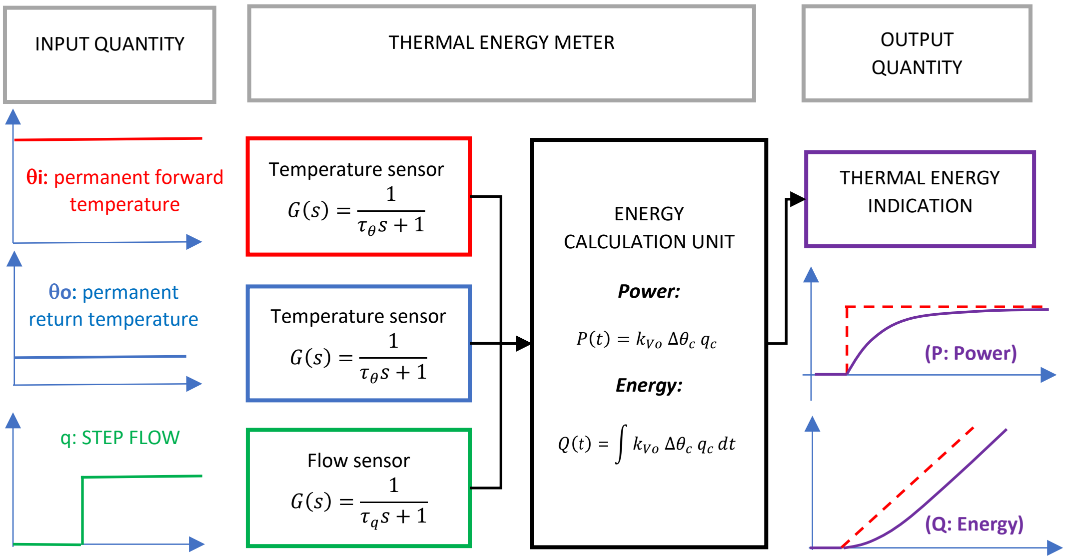


Figure 7

The output registration of energy totalizer over the time elapsed allow the possibility to evaluate the meter response when a flow rate step is applied on input.

Test method:

Here after the step response is presented as one of possible method to investigate the dynamic behaviour of thermal energy meters when the flow rate change. Adapting a conventional gravimetric test rig by adding an ON/OFF in line valve is a reasonable solution to reproduce a “step flow”.

A temperature difference is realized using two thermostatic baths where reference temperature is measured with thermometers with traceability to national standards. Each bath is set to a specific temperature to simulate a difference of temperature.

Before to generate the flow step, both temperature sensors are in equilibrium in two baths. While the temperature difference is stationary the commutation of flow valve starts the test. During this operation a data logger (internal or external) register the energy totalizer during time.

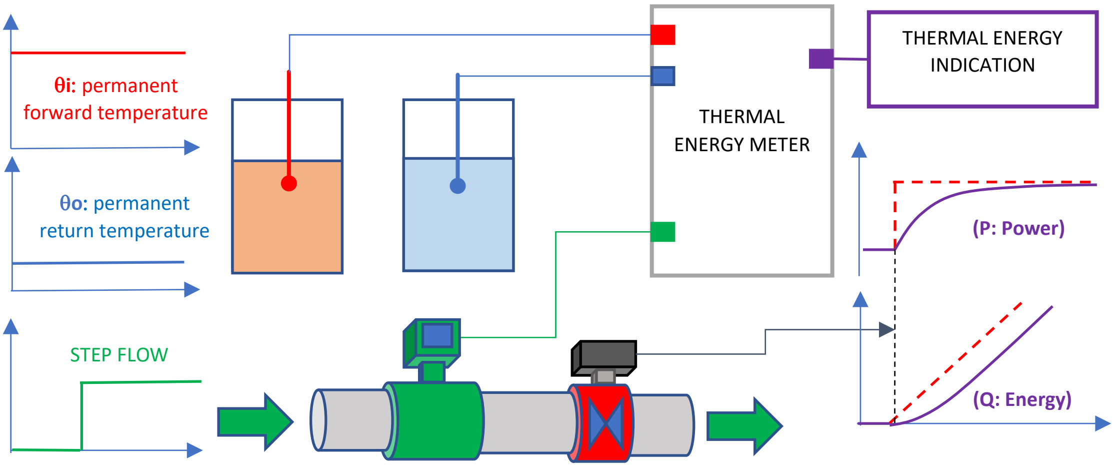


Figure 8

As for previous step temperature test a data set of collected couple of values: time and Energy (t,Q(t)) is available for dynamic properties evaluation.

DATA PROCESSING.

As for previous step temperature and step flow tests, data sets of collected couple of values of time and Energy (t,Q(t)) is available for dynamic properties evaluation.

Before to introduce the analytical method for data processing is necessary to point out some particularities of method that allow some useful simplification.

Is important to highlight that for both step temperature and step flow tests, only one of inputs quantities is changing over time. This test condition reduces to only one branch of measurement chain where only one quantity is subjected to dynamic behaviour.

Next picture show measurement chain where only flow rate is subjected to a step (**q**). Other quantities remain constant during time as temperature difference $\Delta\theta(t) = \Delta\theta_c(t) = \theta i(t) - \theta o(t) = constant.$

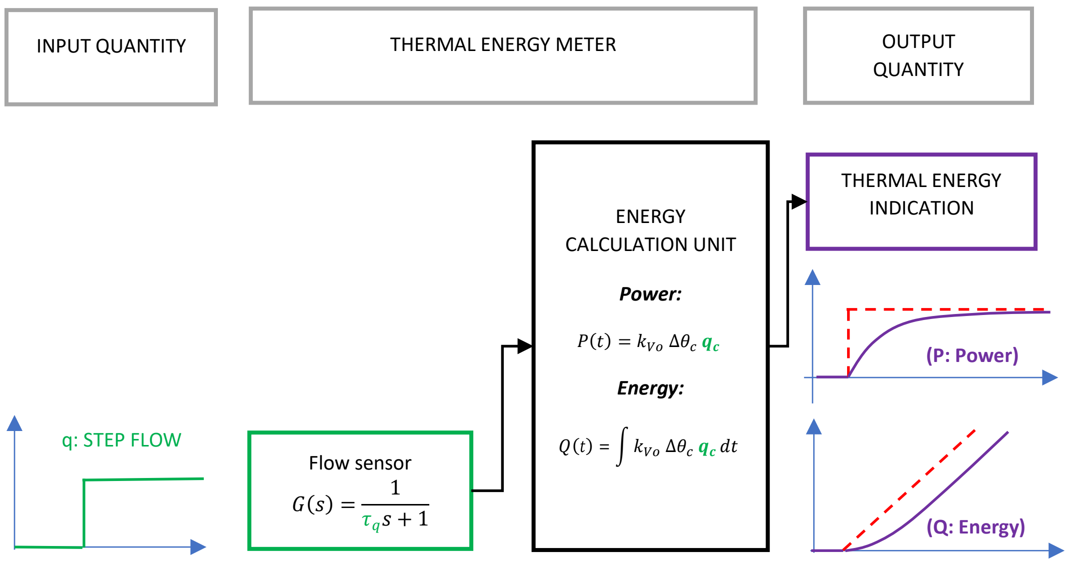


Figure 9

The related transfer function can be written as follow considering input power as:

$$P_{in}(t) = k_{Vo}\,\Delta\theta\, q(t)$$

Equation 2

Where:

$P(t)$ Power [W]

k_{Vo} Heat coefficient [W/(K dm³/s)]

$\Delta\theta$ Temperature difference [K]

$q(t)$ Flow rate [dm³/s]

Laplace transform of input power gives:

$$\mathrm{P_{in}}(s) = \mathcal{L}[\mathrm{P_{in}}(t)] = \mathrm{k_{Vo}}\ \Delta\theta \frac{\bar{q}}{s}$$

Equation 3

Where $\bar{q}$ is flow step amplitude. Is possible to calculate the power output as follow:

$$\mathrm{P}_{out}(s) = P(s)\mathrm{G}(s) = \mathrm{k_{Vo}}\ \Delta\theta\bar{q} \frac{1}{s(\tau_q s + 1)}$$

Equation 4

The difference between power input and power output is given by:

$$\mathrm{P_{in}}(s) - \mathrm{P}_{out}(s) = \mathrm{k_{Vo}}\ \Delta\theta\bar{q}\left[\frac{1}{s} - \frac{1}{s(\tau_q s + 1)}\right] = \mathrm{k_{Vo}}\ \Delta\theta\bar{q}\ \frac{\tau_q}{\tau_q s + 1}$$

Equation 5

Integrating power difference $\mathrm{P_{in}}(s) - \mathrm{P}_{out}(s)$ is possible to obtain energy difference as follow:

$$\mathrm{Q_{in}}(s) - \mathrm{Q}_{out}(s) = \frac{\mathrm{P_{in}}(s) - \mathrm{P}_{out}(s)}{s} = \mathrm{k_{Vo}}\ \Delta\theta\bar{q} \frac{\tau_q}{s(\tau_q s + 1)}$$

Equation 6

Final value theorem give possibility to calculate the difference between input energy and output energy when transient has finished.

$$\Delta Q = \lim_{s\to 0} s\big(\mathrm{Q_{in}}(s) - \mathrm{Q}_{out}(s)\big) = \lim_{s\to 0} s\left[\mathrm{k_{Vo}}\ \Delta\theta\bar{q} \frac{\tau_q}{s(\tau_q s + 1)}\right] = \mathrm{k_{Vo}}\ \Delta\theta\bar{q} \lim_{s\to 0} \frac{\tau_q}{\tau_q s + 1} = \mathrm{k_{Vo}}\ \Delta\theta\bar{q}\tau_q$$

Equation 7

Last equation gives the possibility to measure τ_q by estimating energy difference on a set of data. Recalling that $\mathrm{P_{in}} = \mathrm{k_{Vo}}\ \Delta\theta\bar{q}$ is a known quantity because temperature difference $\Delta\theta$ and flow step amplitude are given, we obtain:

$$\Delta Q = \mathrm{P_{in}}\tau_q$$

Equation 8

And consequently:

$$\tau_q = \frac{\Delta Q}{\mathrm{P_{in}}}$$

Equation 9

Is important to notice that is possible to achieve same result also having a step of temperature and maintaining permanent flowrate.

The above solution of the problem has an interesting graphical explanation as next picture show:

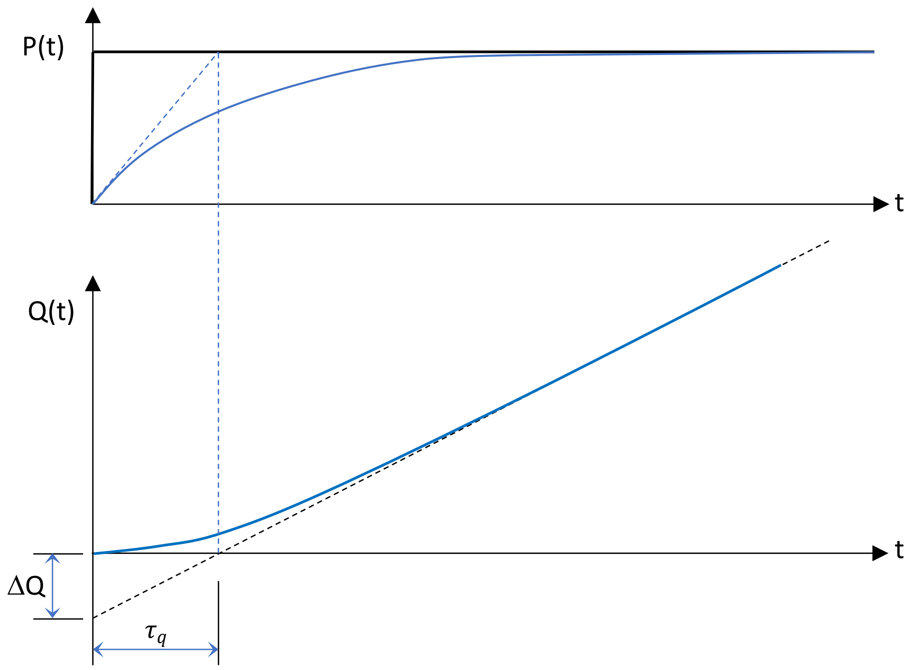


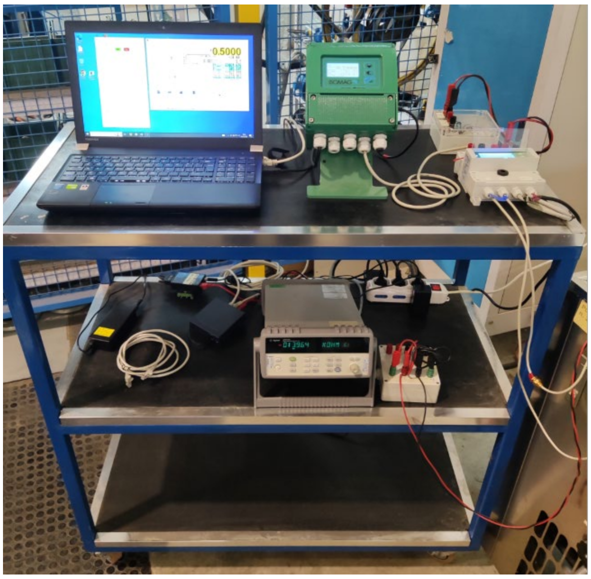
Figure 10

LABORATORY APPLICATION.

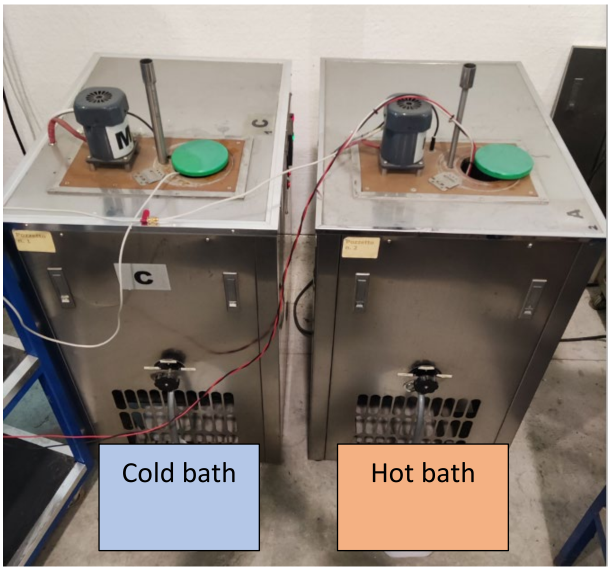
To evaluate the application of test method explained above some measures were done on test facility of Libra LAT 237 Accredited Laboratory. Calibration facility consists of six independent calibration lines applying static weighing method according to ISO 4185:1980. The standard is for volume and mass flow rate calibration quantity and the same standard is used as a reference for calibration of totalized volume and mass. Equipment includes thermostatic bath, thermometers, digital multi meters and other ancillary devices.

Figure 11 – LIBRA LAT237 ACCREDIA Calibration Laboratory

The test set up is composed as next pictures show:



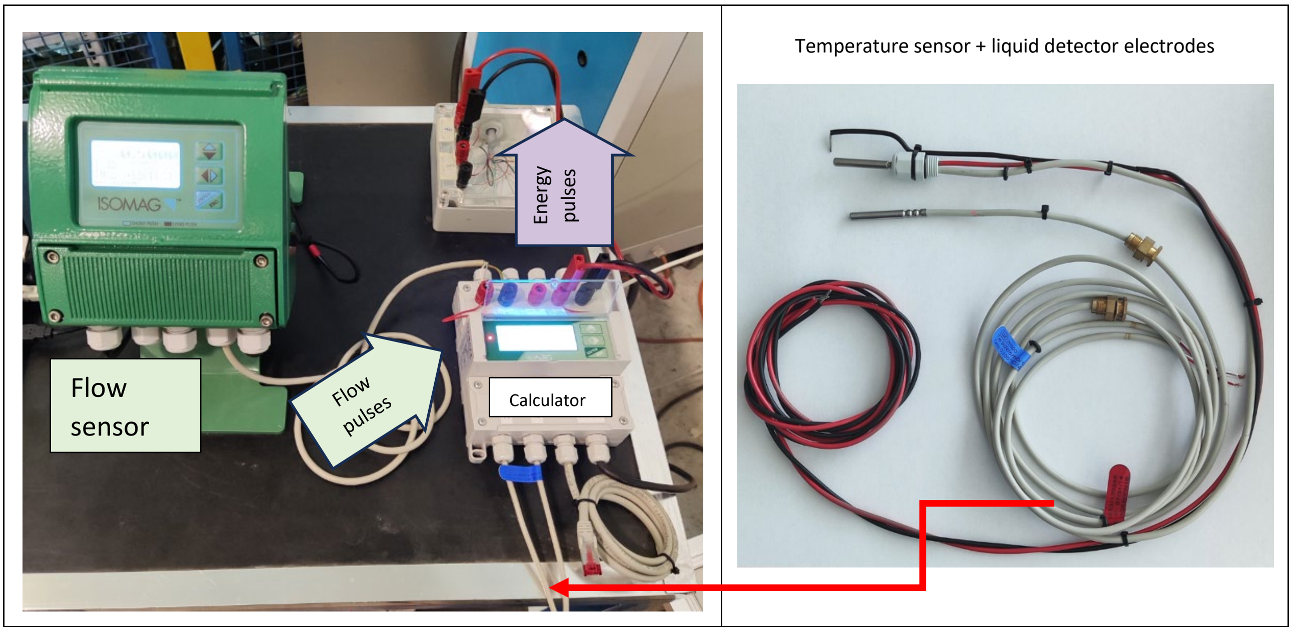
Thermal energy meter (hybrid) + PC data logger



Hot and cold bath

Figure 12 – Test set up

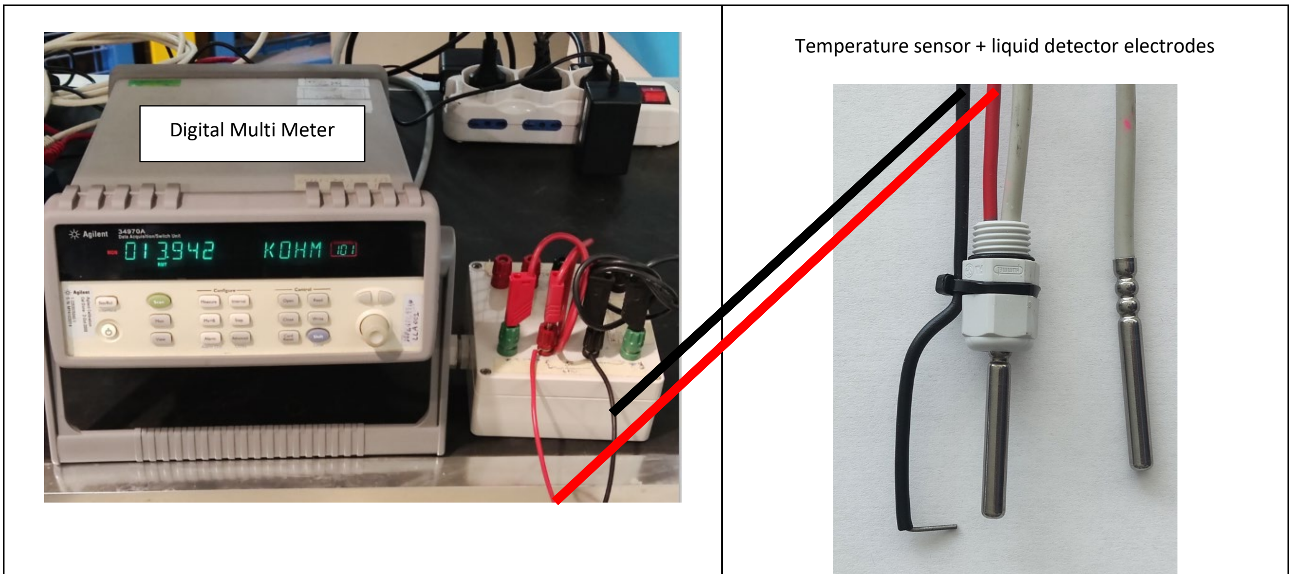
Next pictures explain all parts of equipment used.



Calculator and flow sensor	temperature couple

Figure 13 –Calculator, temperature sensors and flow sensor.

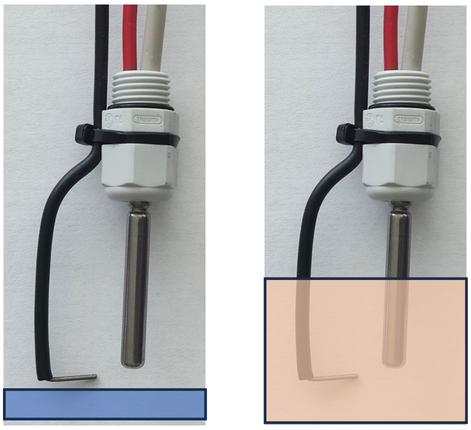
Flow sensor (MV110 ISOIL) pulse output is connected to calculator flow sensor input (conveying liquid). Temperature sensors (PT1000 2wire JUMO type: 902475/50/150) are connected to calculator inputs. Pulse output (energy) is connected to a digital multi meter.



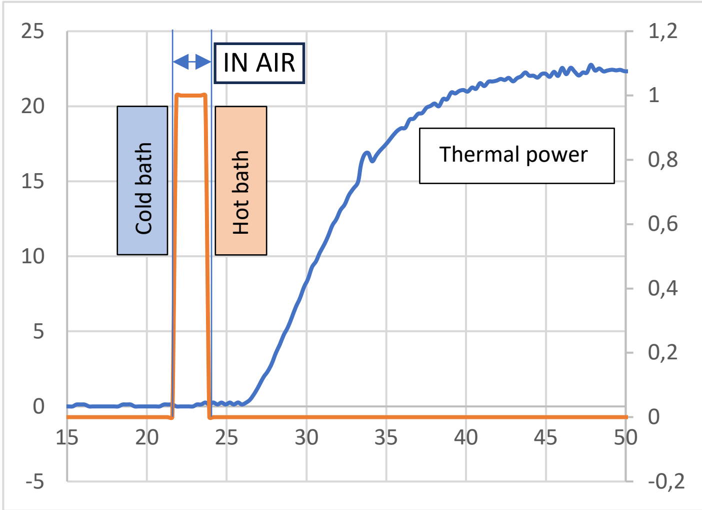
Digital multi meter	temperature couple

Figure 14 – detector electrode

Digital multi meter sense the resistance between the cap of forward temperature sensor and the electrode close to the top of temperature sensor. While the sensor is immersed into a bath (cold or hot) the resistance is of the order of some Ohm. When the sensor is moved from a bath to the other while the sensor is not immersed in the liquid the resistance increase to some kOhm. Because the electrode is close to the sensor the sudden change of resistance reveals the sensor crossing surface between air and liquid. This signal transition is the moment at which start the step of temperature to the thermal sensor.



R>>1Ω (open circuit)	R<<1Ω (closed circuit)



Digital multi meter sense crossing liquid/air	Left axis: Thermal power (kW) Right axis: 0=low resistance (in liquid), 1=hight resistance (in air)

Figure 15 – Detector electrode functioning.

Data logger (pc logger) register both pulses and resistance at sampling rate of about 4Hz.
Next picture shows a sample of test results where temperature difference and applied permanent flow rate gives a thermal power step of about 22,4kW.
Continuous line (blue) is the total amount of energy (as sum of energy pulses) registered during test. A linear regression of total energy on last part of recorded data, where transient is finished, gives the dashed line. The intersection to time axis gives the experimental values of time Δt. This time $\Delta t = \tau(s)$ when dynamic model is well represented by a first order differential equation model.
Otherwise Δt is a time quantity that gives information about the dynamic behaviour of the measurement chain tested. In general, greater Δt means lower responsiveness meters (“less fast”).
Is fruitful to observe that Δt comprises not only dynamic properties of the meter but also internal delay due to other functioning aspect as time sampling, calculus time delay and other issues that have effect on timing of measure.

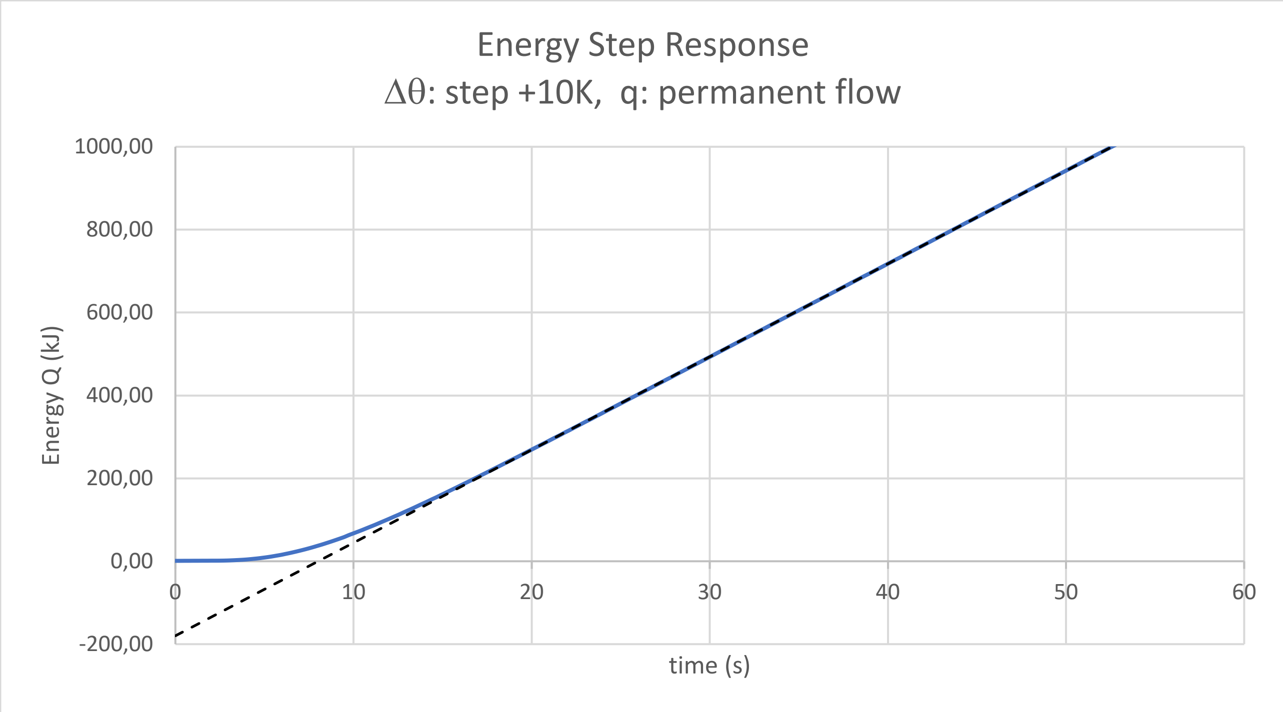


Figure 16 – Energy step test, acquired data.

A zoom close to step is shown in next figure:

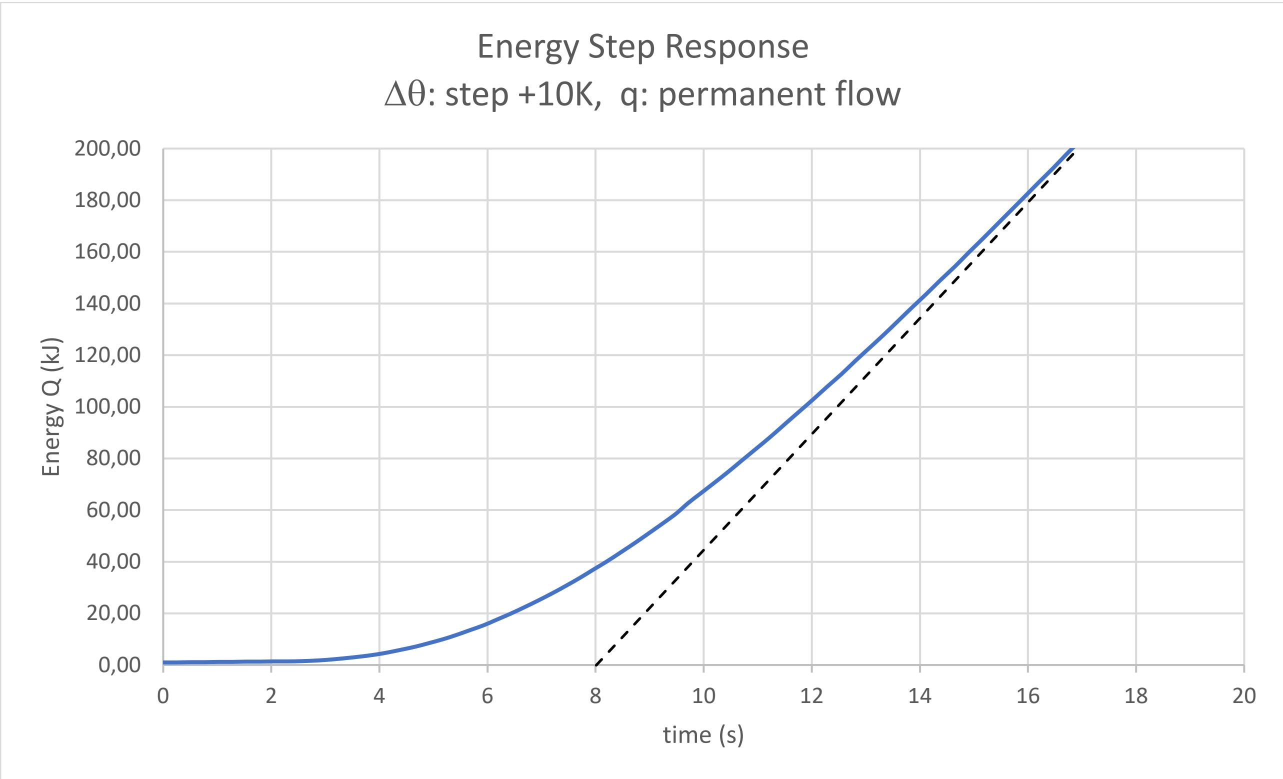


Figure 17 – Energy step test, Δt delay time.

Several tests were done changing flow rate and consequently thermal power as next picture resumes:

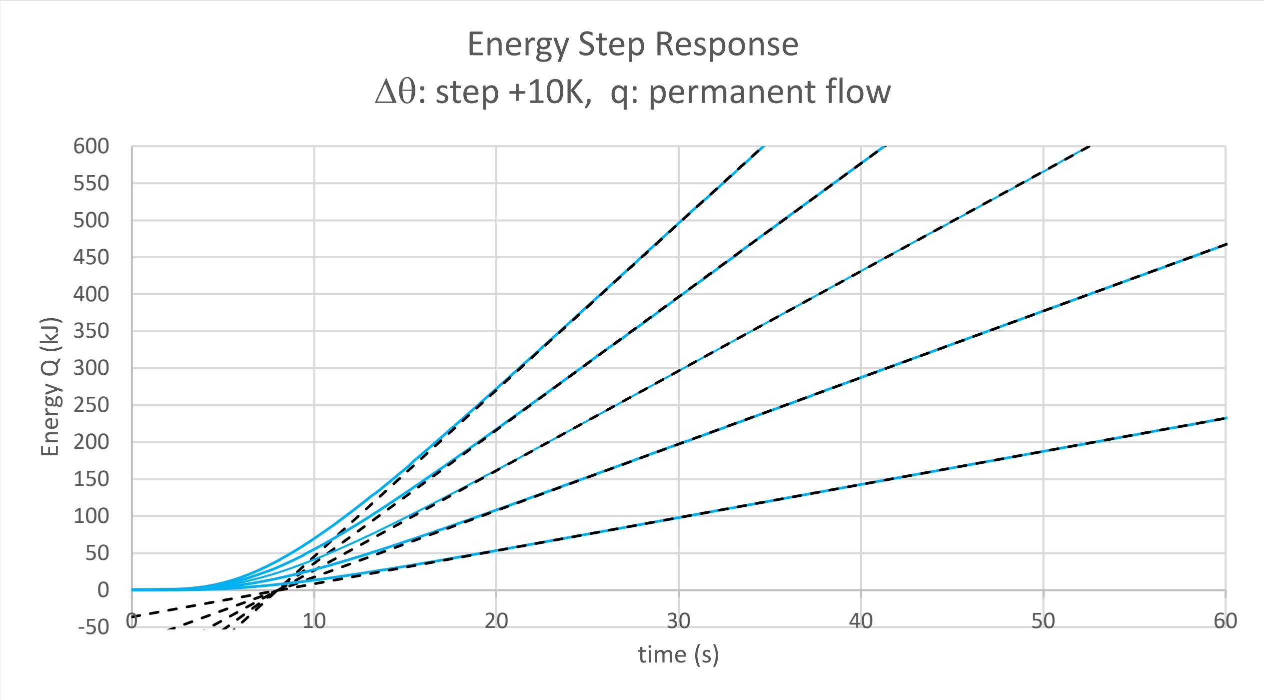


Figure 18 – Energy step test at different power.

A zoom close to step is shown in next figure:

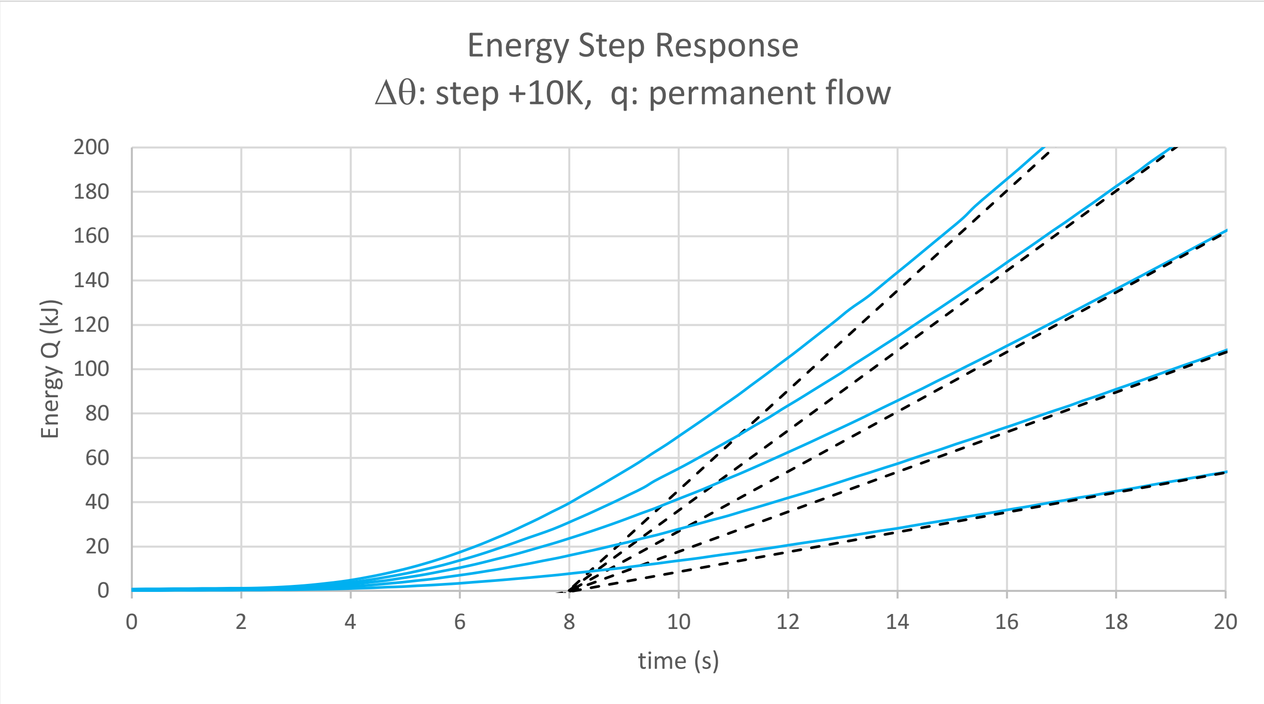


Figure 19 – Energy step test at different power, Δt delay time.

Next table resume result of test done:

Nominal Power	**Δt**
(kW)	**(s)**
22,5	7,98
18,0	7,99
13,5	8,00
9,0	8,03
4,5	8,08

Δt mean (s)	**8,02**
standard dev. (s)	**0,04**

Table 1 – Experimental data results

Experimental data show a good repetition of values indicating that the application of method is robust. Data analysis show a drift of estimated **Δt** according to thermal power. Increasing thermal power a **Δt** reduction is observer of the order of (7,98-8,08)/(22,5-4,5)=-0,0056 s/kW.

CONCLUSION

Energy Step Test method need only few requirements listed below:

1) Energy Step Test can be done through available indication and output devices of thermal energy meters according to actual EN1434. (user interface as display and/or energy pulse output)
2) Energy Step Test performed changing only one input quantity. Inputs are step of temperature or step of flowrate. when one is subjected to a step the other remain in permanent conditions.
3) Minimum data required to implement the method. Basic data list requires the registration of time sequence of energy counted and the zero time as origin which to refer all data transient. (this can be easily implemented by measuring resistance between probe case and liquid.)
4) Simple calculation on data set, is necessary only a linear regression to estimate parameters.

The estimated time parameter Δt (s) can be interpreted in many ways. We can assume Δt = τ(s) when dynamic model is well represented by a first order differential equation model.
Otherwise Δt is a time quantity that gives information about the dynamic behaviour of the measurement chain tested.
Figure 20 explain graphically that step response dynamic effects on energy measure is represented by a time delay of energy counted. The same amount of energy (black line) is achieved late compared to Ideal model. Because Δt represents a delay time is simple to compare quantitatively the properties of meters and, more, is possible to introduce a classification of meters response based on measured time delay.
In general, lower Δt means higher responsiveness of meters ("more fast").
Is fruitful to observe that Δt comprises not only dynamic properties of the meter but also internal delay due to other functioning aspect as time sampling, calculus time delay and other issues that have effect on timing of measure.

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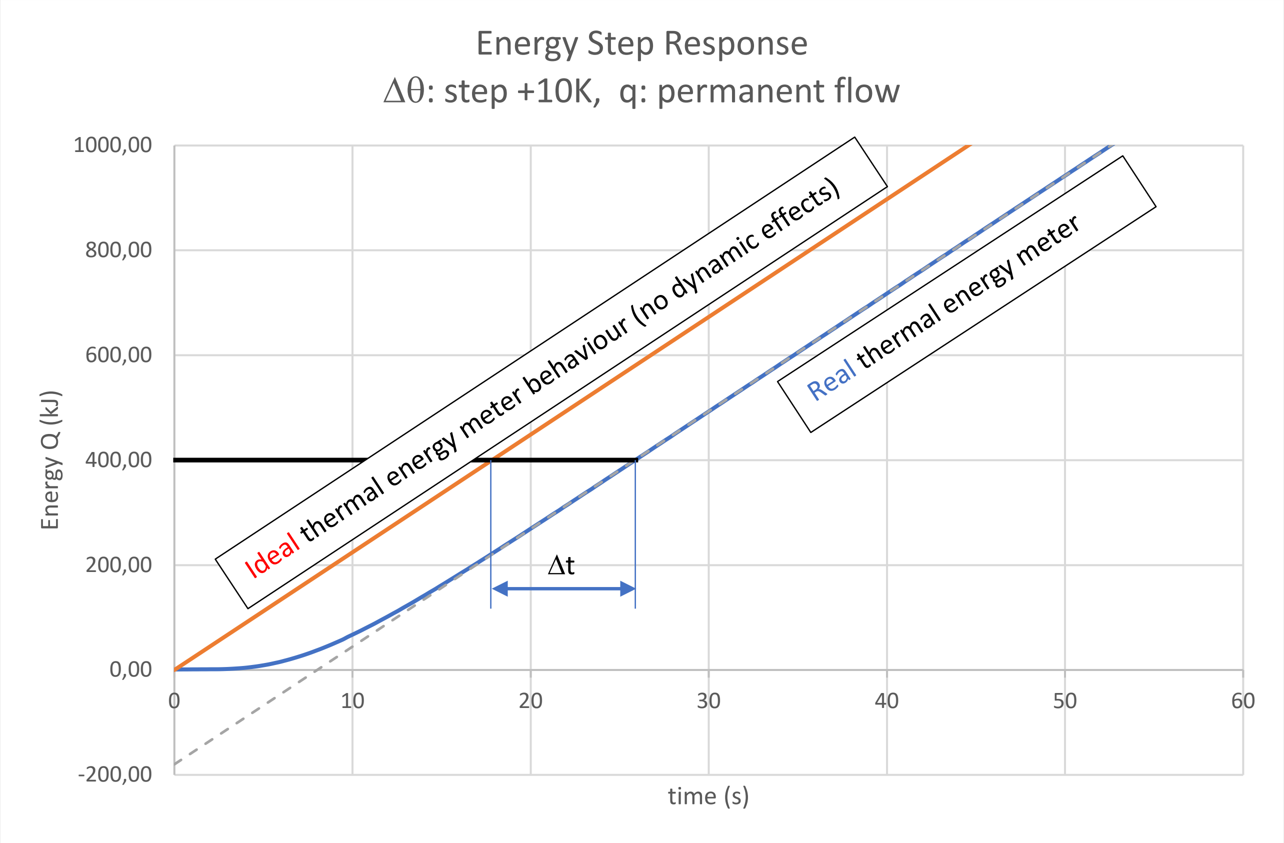

Figure 20 – Energy step test, Δt delay time.

On the other hand, considering data when transient has finisched, is evident a leak of energy counted.

Figure 21 show the leak effect on energy counted far from the beginning of transient.

Is important to notice that energy pulse resolution and frequency are not a critical parameter that affect the method accuracy.

Time delay Δt is linked to linear regression energy logged data. If data are rare or close is not a problem for a good fit result. The only requirement is that logged data are long enough compared to transient time.

In this way we can consider that regression line intersection to time axis (Δt) is not directly affected to energy pulse resolution/frequency or display resolution for indicating devices.

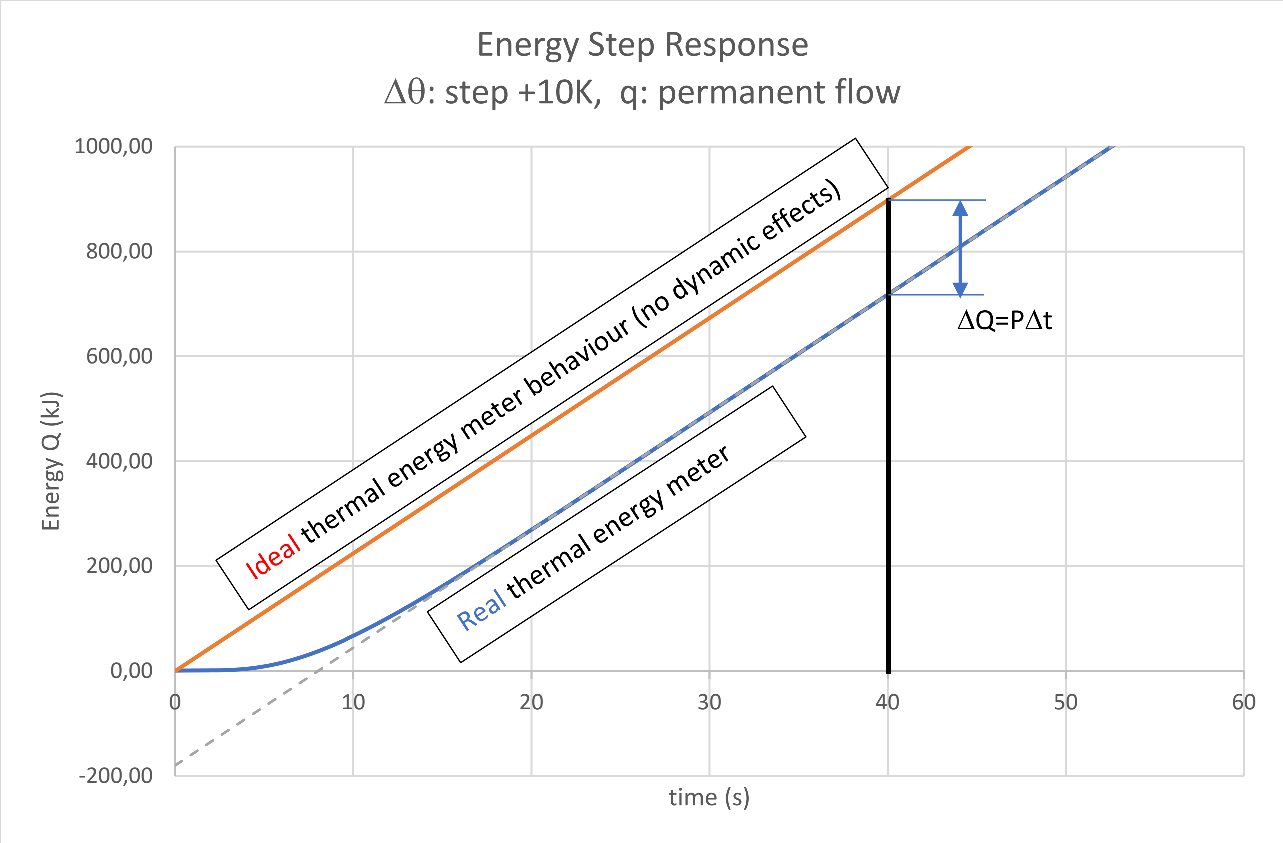

Figure 21 – Energy step test, ΔQ=P Δt energy leak.

Based on present work are still in progress other test to evaluate sensitivity of the method changing all parameters involved. As example will be changed also Δθ maintaining the same flow rate.

Also pulse output resolution will be changed to test sensitivity to this parameter.

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[3] Handbook of Measurement Science, Volume 2: Practical Fundamentals, P.H. Sydenham, R. Thorn 1991 by Wiley

[4] Thermal energy meters with short integration times - BJÖRN FOLKESON, DANIEL MÅNSSON, THOMAS FRANZÉN - ISBN 978-91-7673-561-9 | © Energiforsk January 2019 - Energiforsk AB | Phone: +46-8-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

[5] EN 1434 - Thermal energy meters

[6] Misure termofluidodinamiche. Giorgio Ficco, Marco Dell'Isola, Paolo Vigo (ISBN 9788833594668 Publisched on 2022, May)