

# EXPERIMENTAL ANALYSIS OF RADIATORS' THERMAL OUTPUT FOR HEAT ACCOUNTING

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## Abstract

*Radiators represent the most spread heating body (installed since late 1800s) and in the last decades different radiators typologies have been proposed on the market, characterized by different materials, sizes, shapes, etc. Recent EU Directive on energy efficiency (EED) has set the obligation to install individual meters for space heating in building served by a central heating source. To this aim, when direct heat meters are not technically feasible, indirect systems like heat cost allocators are applied on each radiator in a dwelling and the knowledge of single radiators' thermal output is essential for an accurate and fair heat cost sharing. The EN 442:2014 describes a method for radiators' thermal output measurement whose expanded uncertainty is lower than 1% in reference laboratory conditions. However, radiators' thermal output is strongly dependent on installation and boundary conditions. Thus, to get radiators' thermal output at operating conditions "characteristic equations" are available but, unfortunately, they do not include any possible actual operating condition among which: i) installation position with respect to the wall and the floor; ii) presence of grid/shelf/niche or an obstruction (e.g. caused by curtains); iii) thermo-fluid-dynamic condition variations (inlet flow rate and temperature); iv) hydraulic connections. In this paper, the experimental results of thermal output measurement of different radiators typologies (cast iron, aluminium) at different installation conditions are presented, together with an analysis of the associate technical-economic effects on space heating cost sharing. Reductions of radiators' thermal output up to 15% due to hydraulic connections and between 10% and 20% due to flow-rate variations have been found. Furthermore, different installation conditions showed deviations between operating and standard radiators' thermal output between 5% and 15%.*

Keywords: radiators, heat accounting, thermal output, operating conditions

## 1. Introduction

Directive 2012/27/EU [1] on energy efficiency has set the obligation to install individual meters or indirect systems (e.g. heat cost allocators) allowing individual measurement of energy consumption for space heating in multi-apartment buildings supplied by district heating or common central source. In many cases this obligation, either due to architectural constraints and/or to plant configurations or to

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high costs (e.g. in existing buildings and especially in the historical ones [2]) results in the installation of indirect heat allocation systems, such as Heat Cost Allocators. As well known, such devices are based on the estimation of thermal energy exchanged by single radiators and to this aim, the knowledge of radiator's heat output is crucial.

In recent times, radiators, in addition to their own main functionality, have also assumed a major architectural/esthetical value, which has led to the spreading of different radiators types (each characterized by different material, size, shape, etc.). Unfortunately, only rarely the actual thermal output of installed radiators is consistent with the nominal one, which is measured in the laboratory at rated temperature and at "standard" installation conditions. Besides, radiators are generally installed employing connections, flow rates, positions etc. that may be different from reference standard so determining thermo-fluid-dynamic conditions very different from testing. In order to investigate issues related to indirect heat accounting, it is necessary to consider the heat transfer phenomena involved, the combined radiative-convective effects and, to a negligible extent (unless in case of wrong installation), conduction. Furthermore, actual heat transfer influences the effective temperature distribution on the radiator's surface. Natural convection plays a significant role and represents from 50% to 90% of the overall thermal output depending on the radiator's type. Radiators' thermal output in operating conditions depends on several factors (average external surface temperature; shape, material, size and surface finish; water flow rate etc.) and its knowledge is crucial for effective heating plants sizing and fair heat cost allocation [3]. Radiators are classified as a function of construction material (steel, cast iron, aluminium) and shape (i.e. panel, columns, etc.) [4,5]. The methodology for the determination of radiators' thermal output has been achieved in the last years moving from a manufacturer's statements at the beginning of sixties, to a standard measurement in the seventies, to the recent accurate and rigorous European harmonised standards EN 442-1 [6] and EN 442-2 [7]. Moreover, some of existing heating plants are very old and accurate information about radiators' thermal output is not available or confusing and this can affect the accuracy and fairness of space heating costs sharing required by the EED [1]. To face this problem, different empirical solutions are adopted, in different Countries. The Italian Thermo-technical Committee (CTI) proposed that for indirect heat accounting, the thermal output must be determined in accordance to the following hierarchy: level 1) according to EN 442 (available since 1997); level 2) for heating appliances installed before the entering into force of EN 442, according to available national standards; level 3) for very old plants, if level 1 and 2 are not applicable, thermal output should be determined through non experimental methods if validated (such as the "dimensional method" described by UNI 10200 [8]). Obviously, not-experimental methods are not as accurate as the EN 442 reference method and do not give any possibility of taking in account the dependence of calculated thermal output on installation conditions and actual operating parameters (i.e. water flow rate).

Looking at the scientific literature, only few work are available about the measurement of radiators' thermal output at operating conditions. Brady et al. investigated the on-field effects of decorated covers on radiators finding thermal output reductions up to 40% in the case of wooden cover [9]. A CFD simulation was performed by Embaye [10] with pulsed flow using frequency ranging from 0.0083 Hz to 0.033 Hz and amplitude from 0.0168 kg/s to 0.0228 kg/s. The results of the analysis showed that 25% improvement in the specific radiator's heat output is achievable while maintaining the same radiator target surface temperature of 50°C. Calisir et al. [11] investigated panel radiator heat output under actual operating conditions. They found radiator's heat output is most linearly increasing

with increasing inlet temperature at different connection positions. Furthermore, for lower mass flow-rates higher temperature differences can be obtained although, due to higher mass flow-rates, higher heat outputs are observed in general.

In this paper, the authors present the results of an experimental investigation aimed at the determination of deviation of the radiators' thermal output at operating conditions from reference standard one, that is used for programming indirect heat accounting systems. Such deviation should be useful to predict the effects on the accuracy of heat accounting when indirect systems are adopted and it has not been yet fully investigated in scientific literature. In particular, the following operating conditions have been analysed: i) presence of a grid, a shelf, niche, an obstruction (e.g. caused by curtains on the radiator); ii) installation position with respect to the wall and floor; iii) thermal output variation employing different connections to the plant and different flow rates. In fact, for the first time, the influence of connection types, flow rates, installation conditions, temperature difference (between the heat transfer fluid and the surrounding air) on the radiators' thermal output in operating conditions has been investigated in terms of deviation from the reference standard ones.

Thermal output of different radiators has been determined experimentally in the reference conditions at the "Laboratorio di Misure Ricerche Termotecniche (MRT)" of the Politecnico of Milano and in operating conditions at the "Laboratorio di Misure Industriali (LaMI)" of Università di Cassino e del Lazio Meridionale.

## 2. Thermal output of radiators

The knowledge of radiator's thermal output in standard conditions is essential for space heating costs sharing using indirect systems (e.g. heat cost allocators conforming EN 834 [12]).

For radiators installed after sixties the thermal output value is generally available, determined in compliance with national standard, while for radiators installed after 1997 such value should be determined in conformity with the European standard EN 442 [6, 7]. Unfortunately, for heaters installed in the early sixties it is hard to find standard thermal output values and for this reason different empirical procedures are adopted, which in some cases are not made known. In this scenario, the "dimensional method" described by UNI 10200 [11] is the empirical method adopted in the Italian market to allow the traceability of the heating costs accounting for radiators installed in the early sixties.

### 2.1 The standard method EN 442

The EN 442 [6, 7] allows the thermal output measurement with an uncertainty lower than  $\pm 1\%$ . The boundary conditions are imposed by means of a closed and unventilated test room characterized by five water cooled walls and one not cooled. The radiator under test is exposed to the not cooled wall. All the walls are insulated, so that in this way the thermal testing conditions are independent from the external environment. The standard thermal output  $\phi$  of the radiator under test is obtained at a temperature difference  $\Delta T = 50^\circ C$ , while heat cost allocators require  $\Delta T = 60^\circ C$ . In this condition is also determined the standard flow rate. The characteristic equation of the tested radiator is obtained by regression of the measured data and is given as:

$$\phi = K_m \Delta T^n \quad (1)$$

where  $K_m$  ( $W K^{-1}$ ) is the constant of the radiator and  $n$  is the exponent of the characteristic equation, generally ranging from 1.1 to 1.4, depending on the ratio between the thermal output exchanged by

radiation and by convection. Since radiators are often made up of a number of identical vertical sections (elements or modules), the thermal output of a single element or section is given by:

$$\phi_L = \frac{\Phi}{N_{el}} \quad (2)$$

where  $\phi_L$  (W) is the thermal output of a single module and  $N_{el}$  is the number of elements. In the case the radiators cannot be split, a module corresponds to a radiator having a conventional length of 1 m.

The EN442 standard introduces the concept of “family” of radiators to take into account the size variability of radiators characterized by similar design and construction, made of identical material and presenting the same position of primary fluid connections. In order to reduce the number of models under test, EN442 also introduces the concept of “type” of radiators, that is a group of radiators of similar design whose cross-section remains unchanged while the height or length can vary (or which present the variation of only one characteristic dimension of the heating surface). In accordance with EN 442, the thermal output of radiators of the same type can be obtained from following equation:

$$\phi = K_T \cdot L^a \cdot H^b \cdot q_m^c \cdot \Delta T^{(c_0+c_1H)} \quad (3)$$

where  $K_T$  ( $J m^{-2} kg^{-1} K^{-1}$ ) is the constant of the type,  $a, b, c, c_0$  and  $c_1$  represent the characteristic constants of the radiator,  $q_m$  ( $kg s^{-1}$ ) is the water flow rate,  $H$  (m) is the height,  $L$  (m) is the length and  $\Delta T$  (K) =  $T_m - T_a$  is the difference between the average temperature of the radiator and the temperature of the test environment. The minimum number of models to be tested within a type is determined by the range of heights  $H_r$ (m) =  $H_{max} - H_{min}$ . When the range of heights is lower or equal to 1 m, the minimum number of models to be tested is equal to 3. Otherwise, when  $H_r > 1$  m, the minimum number of models to be tested is 4.

In order to reduce testing costs, taking into account the technical experience gained in the last forty years [13, 14], some simplifications have been accepted at the European standards level. In particular: i) for radiators constituted by elements, a direct proportionality is accepted between the element number and the thermal output; ii) thermal output is assumed independent from water flow rate.

In case of radiators constituted by modules (typically made of steel or presenting a tubular shape) the EN442 requires to test up to 4 models for both the minimum and the maximum length. For each height the thermal output is then obtained by linear interpolation the test results. The thermal output dependence on the flow rate can also be tested by the laboratory on the request of the manufacturer. For a radiator type, assuming a constant width and a neglecting dependence of thermal output on the flow rate, the thermal output is almost linear with length and is obtained in the following simplified form:

$$\phi = K_T \cdot H^b \cdot \Delta T^{(c_0+c_1H)} \quad (4)$$

Such approximation has been validated and accepted since it provides results lower than 2% compared to the measured ones [15]. For each radiator type and model the manufacturers must declare at least the standard thermal output value  $\phi_L$  of a single module and its characteristic equation.

Nevertheless, it is desirable that in modern plants the following characteristic equation should be employed for minimum and maximum length:

$$\phi = K_T \cdot H^b \cdot q_m^c \cdot \Delta T^{(c_0+c_1H)} \quad (5)$$

that allows to properly take into account the influence of water flow rate,  $q_m$ , on radiator’s thermal output and, consequently, space heating cost sharing. Unfortunately, very often equation (5) is not available and the variation of water flow rate is not properly taken into account for heat cost allocation.

## 2.2 Dimensional method UNI 10200

For radiators installed in sixties, the dimensional method is mentioned in the Italian standard UNI 10200 [11] and allows to obtain, through an empirical calculation, the thermal output. Such method is applicable only for radiators with simple structure such as plates or sectional radiators. On the other hand, the method is not valid for convectors, fan coils, radiant panels or other systems based on the forced convection principle. The thermal output  $\phi_{\Delta T60}$ , referred to a 60°C difference between the average temperature of the radiator and the ambient, is obtained from the following relation:

$$\phi_{\Delta T60} = 314 \cdot S + C \cdot V \quad (6)$$

where  $S$  ( $m^2$ ) is a conventional external surface of the radiator,  $C$  ( $W m^{-3}$ ) is a characteristic coefficient of the appliance, experimentally evaluated for some radiator types and available in the UNI 10200 as a function of the radiator type,  $V$  ( $m^3$ ) is the radiator volume. For the calculation of the external surface ( $S$ ) and of the volume ( $V$ ), it is considered the radiator envelope parallelepiped of height  $H$ , depth  $D$  and width  $L$ . As it is evident from equation (6), this method does not allow to determine the flow rate influence on the thermal output and related heat cost allocation.

## 3. Experimental determination of thermal output in operating conditions

The radiator thermal output is inversely proportional to its total thermal resistance which can be expressed through the following relation:

$$R_T = R_i + R_p + R_e \quad (7)$$

where  $R_i$  ( $K W^{-1}$ ) is the internal convective/radiative resistance,  $R_p$  ( $K W^{-1}$ ), is the wall conductive resistance,  $R_e$  ( $K W^{-1}$ ) is the external convective/radiative resistance.  $R_e$  ( $K W^{-1}$ ) value is always higher than  $R_i$  ( $K W^{-1}$ ), that is considerably higher than  $R_p$  ( $K W^{-1}$ ). Therefore, the thermal output  $\phi_{eff}$  exchanged between the external surface of the radiator and the surrounding environment depends mainly from  $R_e$  ( $K W^{-1}$ ). Unfortunately, on the field, thermo-fluid-dynamic conditions can be very different from reference ones (e.g. due to different flow rate, different connections, etc.). Besides, radiators may present operating temperatures that can be different from reference testing ones. Therefore, the actual thermal output should be calculated by applying the following relation:

$$\phi_{eff} = \phi \cdot F = \phi \cdot (F_{\Delta T} \cdot F_{con} \cdot F_{qm} \cdot F_{in} \cdot F_{vr} \cdot F_P) \quad (8)$$

where  $F$  (dimensionless) is the overall correction factor, given by the product of the following dimensionless correction factors:

- i) fluid temperature correction factor,  $F_{\Delta T}$ , that allows thermal output correction when the average temperature difference between heat transfer fluid and environment is different from reference testing value,  $\Delta T_{REF}$  (K);  $F_{\Delta T}$  correction factor is given by the following equation:

$$F_{\Delta T} = \left( \frac{T_m - T_a}{\Delta T_{REF}} \right)^n \quad (9)$$

where  $T_m$  and  $T_a$  (K) are, respectively, the arithmetic average temperature between the inlet and outlet temperature of the fluid which flows inside the appliance and the surrounding air temperature, measured at the centre of the room at a height of 0.75 m from the floor;

- ii) connections correction factor,  $F_{con}$ , that allows thermal output correction when the radiator working connections are different from testing conditions (inlet section is generally located at the top of the heating appliance, while outlet section is located at the bottom);
- iii) average heat transfer fluid flow rate correction factor,  $F_{qm}$ , that allows thermal output correction when thermostatic valves or other controlling equipment are installed;

- iv) heating appliance installation correction factor,  $F_{in}$ , that allows thermal output correction when installation conditions are responsible of significant deviation of thermal output from expected nominal value;
- v) painting correction factor,  $F_{pr}$ , that allows thermal output correction when the radiator is painted with a paint different from the one used during tests; in this regard the standard EN 442 takes requires two distinct tests when the same radiator model painted using matt or glossy paint;
- vi) atmospheric pressure correction factor,  $F_p$ , that takes into account the effect of pressure variation as a function of altitude, according to the following equation:

$$F_p = \frac{1}{(S_k + (1 - S_k) \left(\frac{p_0}{p}\right)^{n_p})} \quad (10)$$

where  $p$  is the barometric pressure measured during the test,  $p_0 = 1013 \text{ mbar}$ , while  $n_p$  and  $S_k$  are available from EN442-2 [7]. Thermal output of different radiators has been experimentally determined in the reference conditions, according to EN 442-1 and EN 442-2, at the MRT of the Politecnico of Milano and in operating conditions at the LaMI of the Università di Cassino e del Lazio Meridionale. In particular, MRT is a European Reference Laboratory for the definition of the procedures of CE Mark laboratories and operates according to EN 442 [16, 17]. On the other hand, the LaMI experimental setup has been specifically designed to test radiators in actual operating conditions and it is composed by: i) a domestic heat generator (with a nominal thermal power of 23.7 kW); ii) an adjustable aluminium frame allowing vertical and horizontal adjustment of the radiator with respect to the wall and the floor; iii) an auxiliary thermo-convector (for the thermal power dissipation and stabilization); iv) a direct heat meter; v) an acquisition and data processing system. Tests were conducted on commercial radiators, selected among the most used types in the last decades and removed from an existing heating plant.

**Table 1. Technical characteristics of the investigated radiators.**

	Material	
	Cast iron	Aluminum
Tipology	Large columns	Finned
Depth (mm)	145	96
N.elements	9 (reduced to 6 and 3)	9
Height (mm)	890	879
Wheelbase (mm)	800	800
Lenght (mm)	60	80
Connections	---	G1
Water content (L)	0.99	0.60
Weight (kg)	9.27	2.13
Thermal power $\phi_L$ (W)	125.50 - $\Delta T$ 50K 161.77 - $\Delta T$ 60K	184.42 - $\Delta T$ 50K 236.04 - $\Delta T$ 60K
Exponent n	1.28243 - 9 elements 1.26662 - 6 elements 1.23768 - 3 elements	1.3535
$K_m$ EN 442 (W/K)	0,8181	0.9252
$C$ UNI 10220 (W/m <sup>3</sup> )	17000	28100

The experimental campaign was aimed to analyse the deviation of the thermal output in operating conditions with respect to the reference testing ones [18,19] and to evaluate the effects of such deviation on space heating costs sharing [2]. On field tests have been conducted on aged radiators

installed by 10-15 years, while in the reference laboratory, both new and aged radiators have been investigated. The technical characteristics of investigated radiators are reported in Table 1. The tests carried out were:

- analysis of the influence of installation conditions (i.e. shelf, grid, niches, obstructions due to curtains, positioning);
- analysis of the influence of connections;
- analysis of the influence of water flow-rate;
- analysis of deviation between the standard thermal output and the corresponding one estimated through the dimensional method.

### 3.1 *Thermal output measurement uncertainty*

Radiators' thermal output in operating conditions has been measured by employing a class 3 Heat Meter [20]. The measurement equation for thermal output is given by the characteristic equation of heat meters:

$$\Phi = K_m \dot{V} \Delta T_{io} \quad (11)$$

where  $K_m$  ( $\text{kJ m}^{-3} \text{K}^{-1}$ ) is the volume-specific heat,  $\dot{V}$  ( $\text{m}^3 \text{s}^{-1}$ ) is the volumetric flow rate and  $\Delta T_{io}$  (K) represent the inlet-outlet temperature difference. The uncertainty affecting measurements,  $u_\Phi$ , has been determined by applying the uncertainty propagation law to measurement equation (11), obtaining the following relation and considering  $K_m$  as a constant:

$$u_\Phi = K_m \left( \sqrt{\left(\frac{\partial \Phi}{\partial \dot{V}}\right)^2 u_{\dot{V}}^2 + \left(\frac{\partial \Phi}{\partial \Delta T_{io}}\right)^2 u_{\Delta T_{io}}^2} + \frac{\sigma}{\sqrt{N}} \right) \quad (12)$$

where  $u_{\dot{V}}^2$  and  $u_{\Delta T_{io}}^2$  are the flow rate and temperature difference standard uncertainties assumed to be equal to 2% of read value and 0.1 K, respectively, while  $\sigma/\sqrt{N}$  is the type A uncertainty contribution, where  $\sigma$  is the standard deviation and  $N$  is the number of acquisitions [21, 22]. The value of the uncertainty is obtained referring to a coverage factor equal to 2 [23]. Uncertainty affecting EN442 measurements is equal to 1% of read value.

## 4. Results and discussion

In this paragraph the authors analyse the difference between on-field thermal output of different radiators, measured at the LaMI, with respect to the corresponding one in reference testing conditions, measured at the MRT according to EN 442 [6, 7]. Experimental investigations were conducted for an aluminium and a cast iron radiator and on-field measurements were conducted in different installation and operating conditions. Besides, the dimensional method described by UNI 10200 [11] was applied to estimate radiators' thermal output in actual operating condition, demonstrating that, in absence of other information, the application of such method produced a deviation with respect to the MRT reference data of about 3.5% in the case of the aluminium radiator and of about 13.5% in the case of the cast-iron radiator. It is important to notice that the dimensional method is not able to take into account the effect of different operating conditions, nor their impact on heat cost allocation.

Results accuracy has been evidenced by comparing different sets of data deriving from on field measurements, measurement in reference testing conditions and the application of the standard UNI 10200. In addition, the estimation of the measurement uncertainties has been punctually performed.

#### 4.1 Effect of the number of sections

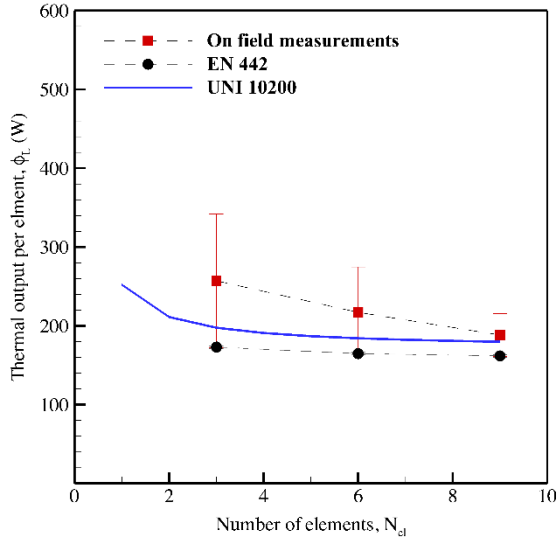
Figure 1 and Table 2 show, for the cast iron radiator analysed, the dependence of thermal output from the number of elements constituting the heating appliance. In particular, in the y-axis of Figure 1 the thermal output for a single element,  $\phi_L$  is reported, obtained by dividing the total thermal output by the number of elements. Error bars in the figure represent measurement uncertainty. Radiators made up of 3, 6 and 9 elements have been experimentally analysed. EN 442 thermal output per element decreases from 173.0W, in the case of a 3-elements radiator, to 161.8W, for the 9-elements radiator, confirming that total thermal output variation with the number of elements is almost linear. Thermal output estimation according to UNI 10200 produces similar results, that are compatible with reference data in the analysed range of 3-6-9 elements, but don't gives results as function of the flow rate.

**Table 2. Thermal output dependence from flow rate and number of elements.**

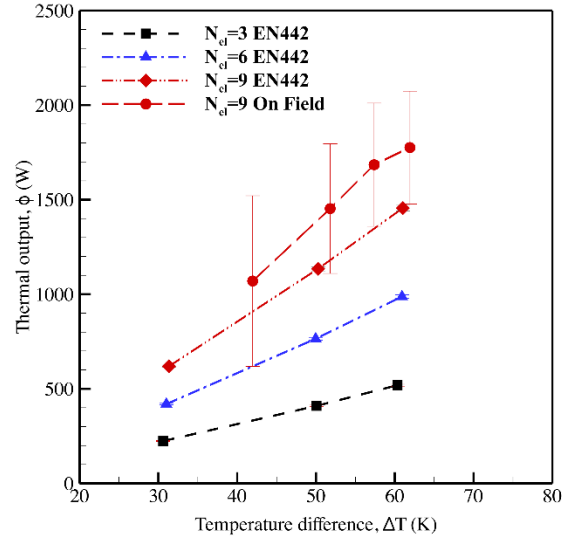
Test 16916 – Cast iron heating body, height 900mm, 4 columns, 3 elements							
		Test EN442			Dependence of $\Phi_C$ from q		
$\Delta T$	K	60.35	50.06	30.60	49,94	49.88	47.63
q	kg/h	34.52	34.63	34.43	280.45	17.93	8.81
$\Phi_C$	W	519.0	409.5	223.6	445.0	394.7	385.0
$\Phi(50)$	W	-	408.9	-	445.7	405.1	396.5
Test 16916 – Cast iron heating body, height 900mm, 4 columns, 6 elements							
		Test EN442			Dependence of $\Phi_C$ from q		
$\Delta T$	K	60.91	48.96	31.01	49.93	50.25	50.28
q	kg/h	65.69	66.04	66.35	291.71	34.20	16.81
$\Phi_C$	W	987.4	764.5	419.4	796.1	753.1	699.6
$\Phi(50)$	W	-	785.2	-	797.5	748.4	713.7
Test 16916 – Cast iron heating body, height 900mm, 4 columns, 9 elements							
		Test EN442			Dependence of $\Phi_C$ from q		
$\Delta T$	K	61.03	50.27	31.33	50.25	49.66	50.15
q	kg/h	99.16	98.61	99.15	286.45	49.57	25.06
$\Phi_C$	W	1456.1	1134.8	619.1	1154.1	1084.9	1059.0
$\Phi(50)$	W	-	1111.4	-	1154.1	1084.9	1059.0

As expected, uncertainty affecting on-field measurements is much larger than uncertainty of EN 442 measurements, mainly because of a relatively low value of the temperature difference  $\Delta T_{i_o}$ , that affects uncertainty according to equation (10). In particular, even though on-field and EN 442 measurements are compatible, on-field measured thermal output significantly deviated from EN 442 value when the number of elements decreases and the temperature difference  $\Delta T_{i_o}$  decreases accordingly. On the other hand, the two measurements are compatible for a number of elements equal to 9.





**Figure 1. Thermal output per element for cast iron heating body from on field measurements, EN 442 and dimensional method (UNI 10200)**



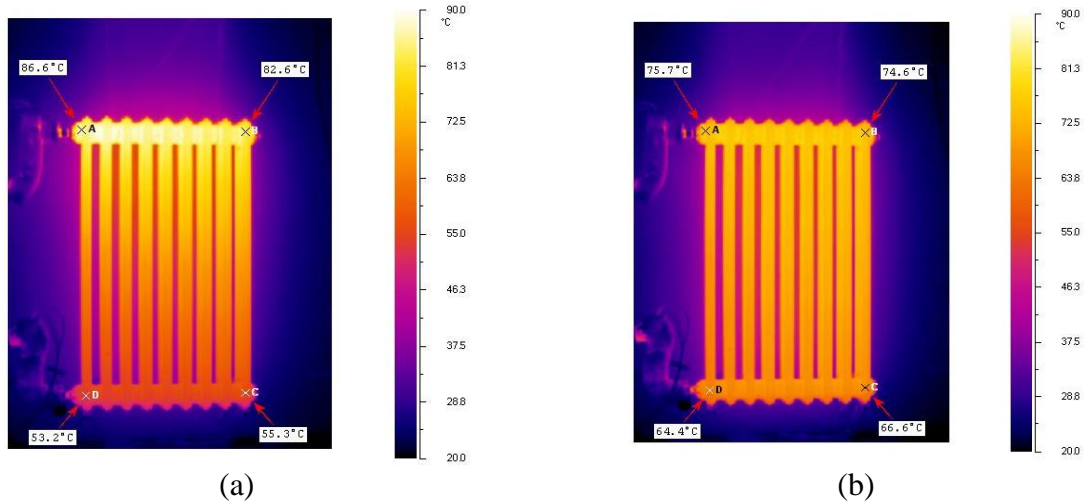
**Figure 2. Thermal output as a function of temperature difference obtained for cast iron heating body from on field and EN 442**

#### 4.2 Effect of the temperature difference influence

Figure 2 shows, for the cast iron radiator analysed, the dependence of thermal output from temperature difference,  $\Delta T$ , between the heat transfer fluid and the surrounding air. As expected in the considered operating temperature range the thermal output,  $\phi$ , is almost linearly dependent on the temperature difference,  $\Delta T$ . EN 442 measurements are available for 3, 6 and 9 elements, while the on-field measurements are only available for the 9-elements case. From the analysis of Figure 2 it can be observed that on-field measurements are compatible with the EN 442 data in the whole range of  $\Delta T$  considered. While the uncertainty affecting measurements at the MRT is constant and equal to 1%, for the LaMI measurements uncertainty increases as the temperature difference decreases. This is due to the decrement of the thermal output when  $\Delta T$  decreases, which corresponds to a reduced temperature difference of the heat transfer fluid between inlet and outlet sections. In particular, for the larger  $\Delta T$  considered the heat transfer temperature drop is equal to about  $\Delta T_{i0} = 3.4^\circ C$ , which decreases to about  $\Delta T_{i0} = 2.0^\circ C$  for the smaller  $\Delta T$  analysed. As a consequence, measurement uncertainty affecting the thermal output,  $\phi$  increases according to relation (12).

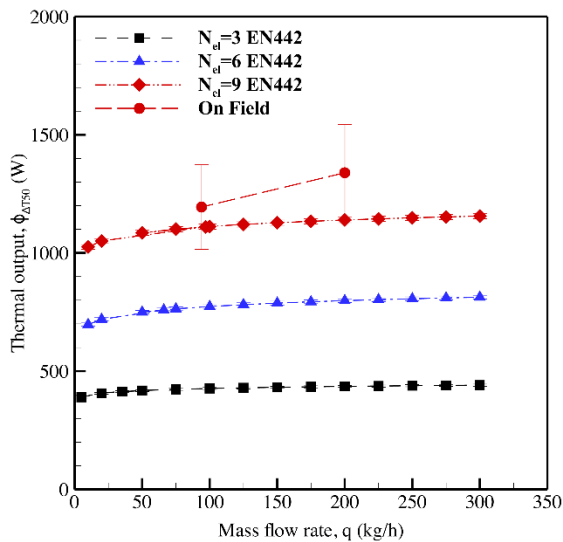
#### 4.3 Effect of heat transfer fluid flow rate influence

Figure 3 shows two infrared images of the 9-elements cast iron radiator obtained at two different water flow rates: a) nominal value,  $q = q_n$ , and b) a quarter of the nominal value,  $q = 0.25 \times q_n$ . From the analysis of such figure, it can be clearly observed that the arithmetic mean temperature is roughly the same for both the cases and for lower water flow rates a better uniformity of the surface temperature of the radiator is obtained. As regards the measurement uncertainties, on-field uncertainty decreases as the water flow rate decreases thanks to the increased temperature difference between inlet and outlet sections of the radiator,  $\Delta T_{i0}$ .

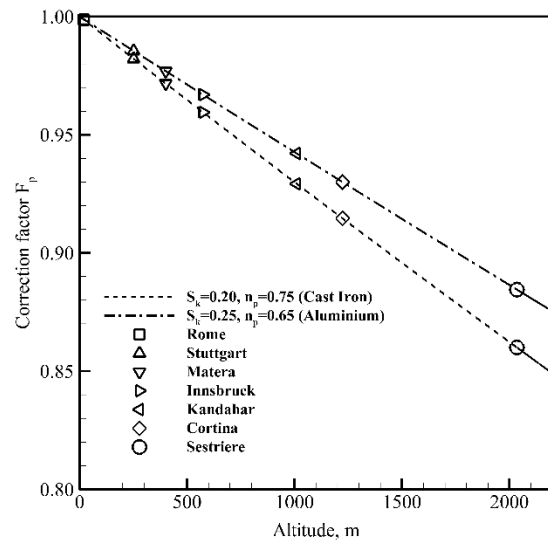


**Figure 3. Infrared (IR) images of the cast iron heating body obtained for different water flow rates: a) water flow rate equal to nominal value,  $q_n$ ; b) water flow rate equal to  $0.25 \times q_n$**

Figure 4 shows the thermal output,  $\phi$ , of the cast iron radiator investigated as a function of heat transfer fluid flow rate,  $q_m$ , for both EN 442 and on-field measurements. MRT measurements are available for 3, 6 and 9 elements, while on-field measurements are reported for the 9-elements case. For water flow rate higher than about  $50 \text{ kg h}^{-1}$  the thermal output slightly increases as the flow rate increases. This is due to the reduced heat transfer fluid temperature drop between the inlet and the outlet sections,  $\Delta T_{io}$ , and a consequently almost constant average surface temperature of the radiator. On the contrary, for water flow-rate lower than about  $50 \text{ kg h}^{-1}$  the water undergoes a larger inlet-outlet temperature drop. As a consequence, the radiator mean surface temperature decreases and the thermal output decreases accordingly. It is important to notice that for a lower heat transfer fluid flow rate larger temperature gradients are evident on the surface of the radiator.



**Figure 4. Thermal output as a function of mass flow rate obtained for cast iron heating body from on field and EN 442 measurements**



**Figure 5. Correction factor  $F_p$  as a function of the altitude**

#### 4.4 Effect of barometric pressure influence

Figure 5 shows the correction factor,  $F_p$ , as a function of altitude. Assuming an atmospheric pressure of 101325 at the sea level, the barometric pressure variation as a function of altitude is calculated according to the following equation:

$$p = 101325 \cdot (1 - 2.25577 \times 10^{-5} H)^{5.25588} \quad (13)$$

Seven towns have been taken as an example for the calculation of the correction factor  $F_p$  according to equation (10). Rome, with an altitude of 20 m by the sea level, Stuttgart with an altitude of about 250 m; Matera, with an altitude of about 400 m; Innsbruck, with an altitude of about 575 m; Kandahar, with an altitude of 1010 m; Cortina D'Ampezzo, whose altitude is equal to about 1225m; and Sestriere, with an altitude of 2035 m by the sea level.

Correction factor  $F_p$  ranges from about 0.999 in correspondence of the altitude of Rome to about 0.865 at the altitude of Sestriere. While barometric pressure decrement due to altitude is not expected to significantly affect radiation, it significantly affects convection. In fact, air density decreases as altitude increases heat transfer coefficient decreases accordingly [24], kept constant other parameters.

#### 4.5 Analysis of different installation conditions

In Table 3 the on-field results of the installation conditions influence tests on the actual radiators' thermal output, for both the aluminium and cast iron radiators, are reported. In particular some common installation were analysed as: i) shelf; ii) niches; iii) grids; iv) vertical and horizontal positioning; iv) obstructions due to curtains on the radiator. The major deviation between the actual thermal output and the standard one have been observed in the presence of a grid for both the analysed radiators. In the case of aluminium radiators, the partial coverage of the radiator causes a reduction of the actual thermal output of about 18% compared to the expected standard value.

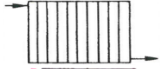






**Table 3. Influence factors of the installation conditions on the effective thermal output**

Installation type	Cast iron			Aluminium		
	wall distance, cm	floor distance, cm	$\Delta\phi\%$	wall distance, cm	floor distance, cm	$\Delta\phi\%$
correct installation	6	11	0.00	2	10.5	0.00
shelf	6	11	0.47	2	10.5	0.18
niche	6	11	-1.83	2	10.5	-6.3
grid	6	11	-16.2	2	10.5	-11
horizontal position	-	-	-	16	10.5	-0.5
vertical position	6	19	-0.29	16	19	2.96
	6	26	0.24	16	26.5	3.87
partial obstruction	-	-	-	16	10.5	-17.7

#### 4.6 Analysis of different connections influence

In Table 4 the on-field results of the connections influence test on the actual radiators' thermal output are reported at high and low flow rates. In particular, the most common connections were analysed, such as: i) mixed flow (inlet left high/outlet right low); ii) counter-current flow (inlet left high/ outlet left low); iii) cross-flow (inlet left low/outlet right low); iv) single pipe with short stemmed valve; v) single pipe with medium stemmed valve; vi) single pipe with long stemmed valve and nozzles; vii) single pipe with long stemmed valve and separator. The higher deviations between the actual thermal output and the standard one were observed with single pipe valve at low flow rate. In such conditions the deviations of thermal output in respect to the reference optimal configuration can be higher than 20%.

**Table 4. Thermal power variation with the connection mode.**

Connection	Scheme	High flow rate (about 200 kg/h)		Low flow rate (about 70 kg/h)	
		$\Phi_{\Delta T 60}, W$	$\Delta\phi\%$	$\Phi_{\Delta T 60}, W$	$\Delta\phi\%$
A (Mixed flow)		1779	0.0%	1770	-0.5%
B (Counter-current flow)				1761	-1.0%
C (Crossflow)		1701	-4.4%	1552	-12.8%
D (single pipe with short stemmed valve)		1527	-14.2%		
E (Single pipe with medium stemmed valve)				1440	-19.1%
F (Single pipe with long stemmed valve and nozzles)		1628	-8.5%	1388	-22.0%
G (Single pipe with long stemmed valve and separator)		1727	-2.9%	1547	-13.0%

## 5. Conclusions

On the basis of measurements, it can be evidenced that radiators thermal output strongly depends on typology and shape, operating conditions (average temperature, water flow rate, pressure) and installation (number of elements, installation position, connection type, presence of grids, shelf, niches or obstructions). The adoption of thermostatic valves and the improvement of building envelope and windows insulating performance determines a reduction of required thermal output from radiators. As a consequence, radiators operate at lower temperatures thus resulting in an improved heating plant efficiency, but such operating condition is not taken into account by international standards for heat cost allocators according to EN 834, that refer to  $\Delta T = 60$  K. The only exception is represented by the mean temperature difference between the heat transfer fluid and the environment, even though such temperature is sometimes not measured and the definition of the reference position is not a simple issue. As a consequence, required overall plant heating output can result underestimated and heat cost allocation for space heating can be inaccurate and unfair. In particular, major issues are associated to: i) connection type adopted, that determines reduction of the radiators' thermal output up to about 15% (in the case of single pipe short-stemmed valve) and between 10% and 20% for flow rates of 30% of the standard flow rate and non-conventional connections (mixed flow or counter-flow); ii) installation conditions that evidence a difference between operating and standard thermal output between 5% and 15%. It is evident that the designer can take into account the above described aspects to correct the standard thermal output declared by the manufacturer in accordance to EN 442. In fact indirect heat accounting according to EN 834 and the UNI 10200 prescribe the adoption of the standard thermal output without any correction. As a consequence, since standard and operating conditions could be significant different, not negligible errors in space heating cost sharing can occur.

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