Individual metering and submetering for cooling application

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Abstract

In 2012 the Energy Efficiency Directive (EED) has set mandatory installation of individual metering and submetering systems for accounting thermal energy consumption in buildings where centralized heating/cooling sources are present, when technically feasible and cost efficient. As a consequence, direct thermal energy meters or indirect heat accounting systems have spread widely in residential buildings, for metering and sub-metering in space heating applications. On the other hand, individual metering of thermal energy in space cooling is a difficult task, due to the very different types of cooling systems and to the lack of technical and legal metrology regulation. In this paper possible solutions available for direct metering and submetering of different types of centralized cooling systems are discussed. Indeed, for direct metering application, the cooling fluid flow metering is a particularly crucial issue due to small pipe diameters and different fluid properties. Thus, the authors carried out an experimental comparison between a Coriolis flow-meter and an ultrasonic clamp-on flow-meter in the cooling fluid circuit of a direct expansion system. Tests have been performed at different operative temperature differences between flow and return, showing relative errors within ± 10%.

1. Introduction

In the last twenty years, increasing attention has been paid to building energy use, given that buildings are responsible for about 40% of worldwide energy use, of which about 40 to 70% is currently due to the space heating. Nonetheless, the energy required for space cooling is growing significantly due to numerous factors, such as incomes and populations growth [1] and the effects of climate change. As a result, the use of air conditioners and electric fans already accounts for about 10% of global electricity consumption. The IEA estimates that, without any action to address energy efficiency, energy demand for space cooling will more than triple by 2050. Hence, energy efficiency of the space cooling sector is of foremost importance, given that most of the space cooling systems have yet to be installed. However, as also highlighted by [2], if increasing the efficiency of building heating systems is already complex, a series of issues make the improvement of space cooling systems efficiency more challenging. Indeed, the cooling load depends on several factors that may change suddenly, such as solar radiation, internal heat gains, urban heat island effect etc. [2].

In 2012, the Energy Efficiency Directive (EED) has set mandatory the installation of individual metering and submetering systems for buildings supplied by centralized heating and cooling systems, given its technical and economic feasibility. The aim is to reduce the waste of energy resulting from the incorrect use of the systems (over-heating or over-cooling), by increasing end-users' awareness.

An individual metering system consists of one or more main meters (installed at the generators) and a set of sub-meters, whose main function is to allocate the energy costs among the end-users. If the energy consumed at the generator (metering level) can be measured simply through direct thermal energy meters, electricity meters, gas meters etc., measuring the energy consumption at the terminal units (sub-metering level) may be more challenging. Indeed, the sub-metering system must be customized to the specific internal unit type and to the thermodynamic properties to be measured. Sub-metering can be performed in two ways: *i)* direct metering, by measuring the actual thermal energy exchanged by the heat transfer fluid with the thermal zones; *ii)* indirect energy metering, by measuring some parameters proportional to energy consumption of a thermal zone (e.g., valve opening times, emission system temperature and similar). The applicability of one technique over the other is related to the type of emission/distribution system and to the economic feasibility of the intervention. The scientific literature regarding heat metering and sub-metering system is quite rich [3], accounting for several issues such as metrological performances [4,5], energy efficiency [6,7], technical-economic feasibility [7], cost allocation [8] etc.

On the other hand, the existing literature on cooling energy metering is almost lacking. This may be due to the limited spread of metering and sub-metering infrastructures both in district cooling networks [2] and in Centralized Cooling Systems (CCS), compared to the heating ones. The available papers address the problem for a specific CCS (e.g., variant refrigerant flow (VRF) systems). As for example, in [9], authors reviewed the methods of individual energy metering for VRF systems. Three new methods were proposed, based on the electronic expansion valve, machine learning and throttling model. In [10] data-driven based estimation of HVAC energy consumption was investigated and a virtual sub-metering system based on a decomposition method was also proposed.

In this context, the aim of this work is twofold: *i)* to provide a brief overview of the available CCS and of the related applicable direct metering techniques; *ii)* to experimentally evaluate the reliability of a clamp-on ultrasonic flow-meter (UF) for measuring thermal energy of a direct expansion system in cooling plant. In fact, although ultrasonic flow meters have great potential, being non-invasive and with limited costs, they present some criticalities, especially in the clamp-on configuration. Moreover, flow metering in cooling application is a critical task, due to the typical small pipe diameters and to different fluid properties. Besides, the adoption of sub-metering systems is always submitted to a cost-benefit analysis and the possibility to use the non-invasive ultrasonic clamp-on technique should be effective to avoid significant initial costs.

2. Direct metering in centralized cooling systems

A CCS includes three main elements: i) a central generation unit, ii) a distribution system and iii) an emission system located in the housing unit. Although there are numerous types of CCS, the characteristics of the applicable metering and sub-metering system essentially depend on the type of heat transfer fluid and of distribution system.

Indeed, the direct metering of the thermal energy Q exchanged by the fluid is based on a simple energy balance, applied to the flow and return sections of the heat transfer circuit, as per equation (1):

$$Q = \int_t \rho \dot{V} (h_{out} - h_{in}) \, dt \qquad (1)$$

where $h_{out/in}$ are the enthalpies in the return/flow sections of the circuit [kJ kg^{-1}], ρ is the fluid density [kg m^{-3}], $\dot{V}$ is the volumetric flow rate of fluid [m^3 s^{-1}] in the time interval dt. To measure the thermal energy exchanged in a CCS, it will be necessary to identify: i) the type of heat transfer fluid and its thermodynamic properties, ii) the type of distribution system, iii) the type and number of terminal units and the related regulation modes (e.g., constant and variable flow etc.). In the following, the CCS and the respective direct metering techniques will be classified basing on the type of distribution which more significantly affects the metering and sub-metering configuration.

As depicted in Table 1, the CCS can be divided into four types, i.e., all-air, all-water, air-water (mixed), direct expansion (DE) and different metering and sub-metring techniques are applicable.

Table 1: CCS classification and applicable metering and sub-metering techniques.

CCS type	**Metering (generator)**	**Sub-metering (terminal units)**
All-air	• TEM (or other generator energy meter) • Electricity meters (renewal air circulators, humidifier, electric battery)	• Insertion flow meters (e.g., Wilson grids) • Enthalpy probes (i.e., temperature and relative humidity probes)
All-water	• TEM (or other generator energy meter) • Electricity meters (circulating pumps etc.)	• TEM
Air-water	• Depending on the needs, it is necessary to combine the measuring techniques of all-water and all-air systems	
Direct expansion	• Electricity meters (fans, compressors, electronics etc.)	• Flow-meter • Enthalpy probe • Electricity meter (fans, electronics etc.)

2.1 All-air systems

In the all-air systems, the regulation can take place either by acting on the inlet temperature (constant air volume - CAV systems) or through a change in the air flow (variable air volume VAV systems). Both CAV and VAV systems can be associated to a single duct or to a double duct distribution system. The basic all-air system consists of: i) a generation system; ii) one or more air handling units (AHU); iii) air distribution channels; iv) inlet and extraction vents. In all-air systems, the measurement of the thermal energy at the sub-metering level must be carried out according to equation (1), by using enthalpy probes (i.e., temperature and relative humidity probes) and either mass or volume flow meters.

Depending on the specific configuration of the all-air system, the following conditions can be distinguished:

a) Multi-zone systems with dedicated AHU for each housing unit; in this case the sub-metering can be carried out by measuring the thermal energy on the primary water circuits of the hot/cold coils of each AHU and, possibly, also the electricity needed for humidification or auxiliary system;

b) Multi-zone VAV systems, with central AHU serving several housing units; in this case it is necessary to measure the inlet air flow in each housing unit, and, depending on the situations, the relative inlet enthalpy (also the relationship between the recirculated air flow rate and the inlet air flow rate should be known);
c) Multi-zone CAV systems with AHU serving several housing units; in this case it is necessary to measure the enthalpy of the humid air in the delivery and return channels of the individual users, provided that the air flow rate is known and constant;
d) Multi-zone systems with double hot/cold ducts; in some cases, the flow rates and therefore the thermal power can be measured separately before the mixing section, in others it is possible to measure only after the mixing section.

By way of example, in Figure 1 a single duct all-air multi-zone variable flow system with a central AHU serving multiple users is represented together with the configuration of the applicable direct sub-metering system.

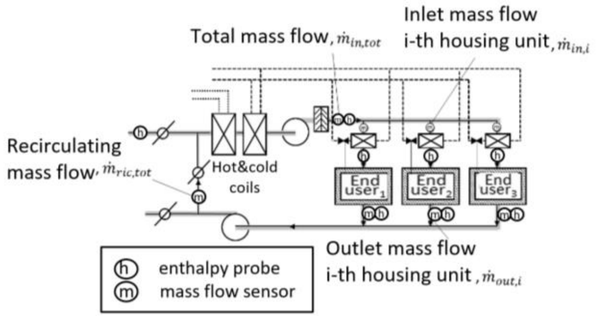


Figure 1: Direct sub-metering system in a single duct all-air multi-zone variable flow system with a central AHU

In the case of simple systems operating with a single duct, as the one reported in Figure 1, and the air mass flow rates in each zone constant, the energy consumption of each i-th housing unit Qi can be carried out on the basis of the energy balance on the aeraulic system, as per equation (2).

$$Q_i = \int \dot{m}_{\mathrm{in,i}} \left(\left| h_{\mathrm{in,i}} - \left(1 - \frac{\dot{m}_{\mathrm{ric,tot}}}{\dot{m}_{\mathrm{in,tot}}}\right) h_{\mathrm{ext}} - \frac{\dot{m}_{\mathrm{ric,tot}}}{\dot{m}_{\mathrm{in,tot}}} h_{\mathrm{out,i}} \right| \right) dt \qquad (2)$$

where $\dot{m}_{\mathrm{in,i}}$ ($\dot{m}_{\mathrm{out,i}}$) is the inlet (outlet) air mass flow rate in the i-th housing unit, [kg s^{-1}]; $\dot{m}_{\mathrm{in,tot}}$ is the total air mass flow rate circulating in the system, [kg s^{-1}]; $\dot{m}_{\mathrm{ric,tot}}$ is the total air mass flow rate re-circulated in the system, [kg s^{-1}]; $h_{\mathrm{in,i}}$ ($h_{\mathrm{out,i}}$) in the enthalpy or the inlet (outlet) air mass flow rate in the i-th housing unit [kJ kg^{-1}]; h_{ext} is the enthalpy of the outdoor air, [kJ kg^{-1}]; t is the time, [h]. The equation (2) is valid for both heating and cooling modes.

In VAV systems, it is possible to reduce the costs of the individual metering system, although accepting a lower accuracy, by considering the enthalpy of the outlet air of each i-th housing unit constant and equal to the conventional comfort value ($h_{\mathrm{out,i}} = h_{\mathrm{out,tot}}$). Similarly, in the case of systems without local post-heating, it is possible to set constant the enthalpy of the inlet air of the i-th housing unit ($h_{\mathrm{in,i}} = h_{\mathrm{in,tot}}$). In this way, the sub-metering system would be composed only by the inlet air flow rate meters and by three enthalpy probes ($h_{\mathrm{in,tot}}$, $h_{\mathrm{out,tot}}$, h_{ext}).

Similarly, in CAV systems, it is possible to reduce the costs by considering known and constant the inlet air mass flow rates $\left(\dot{m}_{\mathrm{in,i}} = \dot{m}_{\mathrm{in,design,i}}\right)$ and by measuring only the enthalpies of the inlet and outlet air of each housing unit ($h_{\mathrm{in,i}}/h_{\mathrm{out,i}}$) and the enthalpy of the outdoor air (h_{ext}). As regards the distribution losses, this can be obtained by difference from the total consumption (i.e., total energy supply) and those measured in all the housing units.

2.2 All-water systems

In the all-water systems, a water solution with additives is used as heat transfer fluid. Chilled water is circulated for cooling, while hot water is circulated through coils for space heating. The basic all-water system consists of: *i)* a generation system; *ii)* water distribution pipes (which can be 2-pipes and 4-pipes systems); *iii)* emission systems (which can be either fan-coils, convectors or radiation systems). In all water systems, the measurement of thermal energy can be carried out by means of equation (2).

$$Q = \int_t \rho \, \dot{V} \, \bar{c}_p \, (T_{out} - T_{in}) \, dt \qquad (2)$$

Where $T_{out/in}$ are the return and flow temperatures, respectively [K], $\bar{c}_p$ is the average specific heat of the heat transfer fluid [kJ kg^{-1} K^{-1}]. A thermal energy meters (TEM), consisting of a flow-meter, a temperature sensors pair and a calculator, can be used for these purposes. In all-water systems different terminal units may be used as emission systems: from the simplest containing a single coil with hot and/or cold functions (radiators, convectors, fan coils, radiant panels etc.), to the most complex, containing multiple coils. Thus, the energy consumption for space cooling and/or heating purposes can be measured in different ways depending on the desired accuracy. For each terminal unit, the following quantities should be measured:

a) thermal energy subtracted for cooling and dehumidification (if applicable) on the cold coil;

b) thermal energy provided for heating, post-heating and humidification (if applicable).

As regards the electricity supplied for ventilation and auxiliary units (for example humidification and post-heating), the connection is supposed to be made directly to the end-user electricity meter. If not, these should be measured separately. In this configuration, at least one TEM must be provided for the hot/cold coil (see Figure 2).

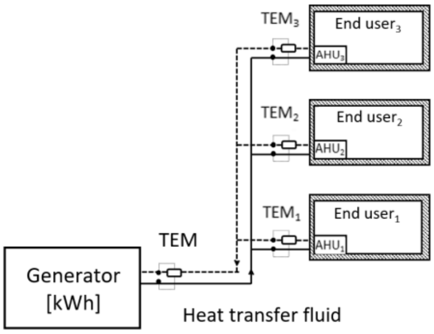


Figure 2: Direct metering configuration, all-water system

In the presence of terminal units with double heat exchanger, the energy consumption for cooling and heating purposes should be measured separately, and this is possible in modern TEMs.

2.3 Air-water systems

Air-water systems represent a hybridization of all-air and all-water systems, in which chilled water and/or hot water is produced and distributed to the terminal units, as in all-water systems, and, separately, primary air is distributed from a central system to the individual zones. In this way, terminal units (which can be of the same types of the all-water systems) provide cooling or heating in each zone, while an AHUs supply ventilation air directly into the zones. Thus, to design the individual metering system, it is necessary to combine the different techniques already described for all-air and all-water systems, considering the specificity of system configuration.

2.4 Direct expansion systems

DE systems (also called mono/multi split air conditioning systems), are divided into two types: VRV (variable refrigerant volume) and VRF (variable refrigerant flow). They consist of an outdoor unit, equipped with a compressor and of a heat exchanger (which may operate indifferently as a condenser and evaporator), and a series of indoor units (splits) each equipped with fan, heat exchanger, electronic thermostatic valve and diverter valve. The connection between the indoor and the outdoor units may be realized by means of two or three pipes distribution system. Figure 3 shows an example of a three-pipe VRV/VRF system and the respective applicable individual metering system.

The flow meter and the temperature sensors can be installed externally to the individual units (split), while on the central external unit the pressure sensors can be installed directly at the inlet/outlet of the compressor (or either on the delivery and return pipes). In this way, it is possible to measure the energy consumed at each housing unit Qi as per equation (3).

$$Q_\mathrm{i} = \int \left(\rho_\mathrm{R}\, \dot{V}\, \Delta h\right)_\mathrm{i} dt \qquad (3)$$

Specifically, by measuring:

- the outlet (inlet) pressure of the compressor and the inlet (outlet) refrigerant fluid temperatures at the internal units, the inlet (outlet) enthalpy at the single internal unit (split) can be calculated;
- the flow rate $\dot{V}$ of the refrigerant fluid at the inlet of the single internal unit (split) and, by knowing the refrigerant fluid density (ρ_R), the consumption of each internal unit can be determined.

With reference to the simplified metering system in Figure 3, it should be noted that the pressure at the compressor inlet could be slightly different from that at the outlet of the indoor unit, with a consequent variation of the outlet enthalpy estimation.

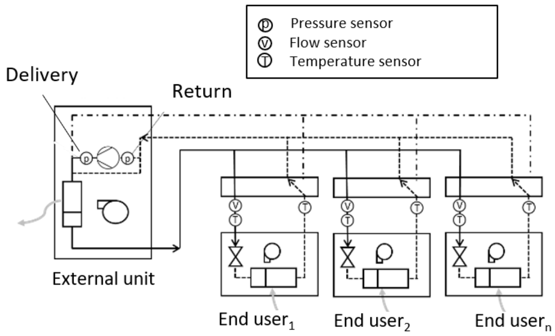


Figure 3: Direct metering configuration, DE system

3. Experimental setup and tests

As evident from Table 1, the direct thermal energy metering in CCS can be performed mainly through TEMs, enthalpy probes, temperature probes, electric energy meters and flow-meters. In particular, flow meters can be used as separate sub-assemblies of a TEM (thus, both at the metering and sub-metering level) or as an energy cost allocation tool (sub-metering level).

In this context, the authors designed and developed an experimental campaign aimed at assessing the reliability of a clamp-on UF meter in the cooling circuit of a DE system, in comparison with the more proven technology of Coriolis flow-meter. The DE system is equipped with a hermetic rotary scroll volumetric compressor, with a displacement of 10.8 cm^3 and capable of providing a nominal cooling capacity of 2.55 kW with AC operation at 220 V and 50 Hz single-phase. The lamination is realized through a thermostatic expansion valve (TEV) with external equalization of operating temperature range [-40 °C; 10 °C] and max operating pressure of 45.5 bar.

The UF (see Figure 4), manufactured by ISOIL Industria and whose declared accuracy is within the range 1-3%, was installed downstream of the condenser, where the refrigerant fluid R410A is at liquid state. The installation and sensor's configuration have been performed according to the manufacturer's instructions. In particular, the UF meter was installed sufficiently far from elbows and bends of the pipe (i.e., copper pipe 10 mm diameter and 1 mm thick, without insulating coating). The fluid properties, and specifically the fluid density, have been calculated via Refprop 10 software [11], depending on the specific operating conditions.

Figure 4: The flow Ultrasonic clamp-on flow-meter

A Coriolis Mass Flow meter (CMF) was installed upstream of the compressor, where the refrigerant fluid is in the superheated vapor phase. The declared accuracy of the CMF is within 0.35%. Figure 4 illustrates the experimental setup and the meters positioning.

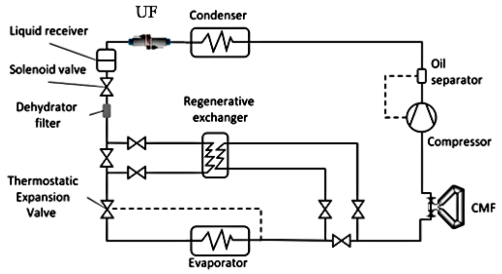


Figure 5: Plant layout of the test rig used, showing the Coriolis Mass Flow meter (CMF) and Ultrasonic Flow meter (UF)

The tests were performed at two different environmental conditions and three different compressor rotation speeds (controlled by an inverter at power frequency of 30, 40 and 50 Hz) for a total of six operating conditions. The different environmental temperature conditions refer to 23/29 °C of the fluid entering the evaporator/condenser respectively (first setup) and 20/35 °C (second setup). These test setups allowed the system to work at different mass flow rates, aiming at evaluating the reliability of the UF meter in a wide operation range.

4. Results and discussions

In Table 2, the results of the tests are reported. For each operating condition, three tests were conducted to verify repeatability and the relative percentage error (RE) was calculated. The reported mass flow values are obtained by averaging the values (n) recorded over the testing time. Indeed, during some tests, an anomalous trend was registered in the coupling signal of the UF meter, probably due to the fact that the pipe diameter where the sensors were installed is at the lower limit of the UF meter range.

As shown in Table 2, the UF meter did not show a good repeatability, except at 29-23 °C and at 50 Hz and 40 Hz and the absolute RE exceeded 10% in 5 out of 18 tests. In other 6 tests the absolute RE was between 5 and 10%.

Table 2: Tests results of CMF meter and UF meter.

Inlet temp. [°C]	*Outlet temp. [°C]*	*Freq. [Hz]*	*Test*	*n*	*CMF meter [kg/min]*		*UF meter [kg/min]*		*RE [%]*
					Avg.	*St.dv.*	*Avg.*	*St.dv.*	
23° C	29° C	30 Hz	#1	155	0.542	0.012	0.503	0.040	-7%
			#2	181	0.553	0.005	0.509	0.038	-8%
			#3	197	0.557	0.005	0.655	0.063	18%
		40 Hz	#4	189	0.681	0.029	0.762	0.085	12%
			#5	218	0.693	0.008	0.729	0.123	5%
			#6	238	0.694	0.007	0.722	0.098	4%
		50 Hz	#7	234	0.817	0.000	0.844	0.096	4%
			#8	214	0.814	0.004	0.822	0.088	1%
			#9	254	0.814	0.005	0.810	0.050	-1%
20° C	35° C	30 Hz	#10	169	0.515	0.003	0.482	0.036	-6%
			#11	160	0.516	0.003	0.494	0.036	-4%
			#12	158	0.514	0.004	0.644	0.054	26%
		40 Hz	#13	200	0.656	0.004	0.664	0.110	1%
			#14	216	0.655	0.005	0.639	0.053	-2%
			#15	209	0.659	0.005	0.793	0.061	20%
		50 Hz	#16	374	0.761	0.004	0.763	0.077	0%
			#17	236	0.768	0.004	0.699	0.050	-9%
			#18	352	0.762	0.005	0.865	0.053	14%

It should be highlighted that, in the majority of the tests, an oscillating trend in the mass flow measured by the UF meter was observed (see Figure 6). This may be attributable to the plant layout and to the UF positioning (i.e., at the condenser outlet and before the liquid receiver). Indeed, the UF meter could be affected by any presence of steam caused by partial condensation of the refrigerant fluid and by the cyclic modulation action of the TEV.

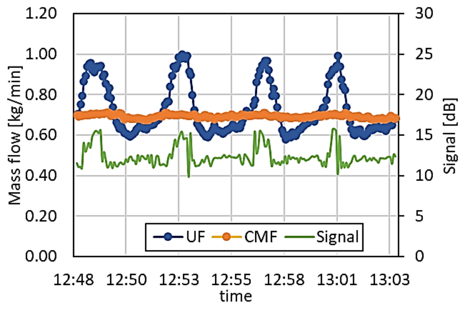


Figure 6: Trend of the measured mass flow rate (test #4)

In Table 3, the authors reported the results of a metrological analysis aimed at assessing the compatibility of UF and CMF through the calculation of the normalized error in equation (4).

$$E_{\mathrm{n}} = \frac{|X_{UF}-X_{CMF}|}{\sqrt{U_{UF}^2+U_{CMF}^2}} \qquad (4)$$

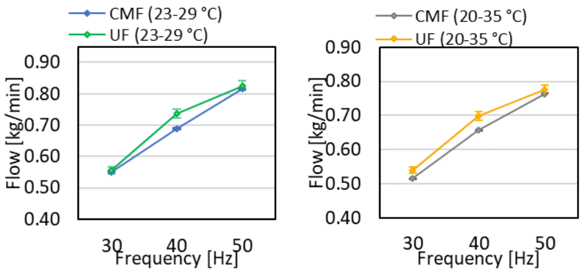
where X_{UF} and X_{CMF} are the average measurements obtained through UF and CMF respectively and U_{UF} and U_{CMF} are their corresponding expanded uncertainties. According to [12] compatibility is demonstrated when E_n in equation (4) is lower than 1.

To this aim, the expanded uncertainty (k=2) of both the CMF and UF flow-meters was roughly estimated according to [13] , leading to an average uncertainty value (including the declared accuracy and type A contributions) ranging 0.20-0.27% and 1.79-1.98% for the CFM and UF meters, respectively. From the analysis of Table 3 and Figure 7 it can be highlighted compatibility is demonstrated only in three out of six operating conditions. In the remaining three cases, full incompatibility of the measurements is evident.

Finally, as shown in Table 3, the RE calculated on the average values exceeded 4.0% in three out of six operating conditions, reaching a maximum value of 7.0%, showing a systematic overestimation.

Table 3: Summary results of CMF meter and UF meter.

Temp. [°C]	Freq. [Hz]	CMF [kg/min]	U_CMF [kg/min]	UF	U_UF [kg/min]	RE [%]	E_N
23-29	30	0.551	0.001	0.556	0.010	0.9%	0.489
	40	0.689	0.002	0.738	0.015	7.0%	3.301
	50	0.815	0.002	0.826	0.015	1.3%	0.689
20-35	30	0.515	0.001	0.540	0.010	4.8%	2.494
	40	0.657	0.001	0.699	0.013	6.4%	3.158
	50	0.763	0.002	0.776	0.014	1.6%	0.880



(a) **(b)**

Figure 7: Compatibility analysis between UF and CMF measurements: (a) 23-29 °C; (b) 20-35 °C.

4. Conclusions

This paper aimed to both provide a brief overview of the available CCS and of the related applicable direct metering techniques and to experimentally evaluate the metrological performance of an ultrasonic clamp-on flow-meter applied in the cooling energy metering of a DE system. According to the analysis, cooling metering and submetering in CCS require a careful analysis of the plant layouts in order to identify the correct applicable metering system, which also satisfies the cost-optimality criterion. Although clamp-on UF meters represent a valid and versatile alternative from both technical and economic feasibility points of view, the experimental analysis presented in this paper has shown that the error of those meters can reach values higher than 10%, especially if the meter is installed on small diameters (e.g., the typical diameters of a distribution system) and the average flow rate of the fluid is low. Such errors are not admissible in the Legal Metrology field, however, UF meters can still be a valid alternative for sub-metering applications, given the effects of the error compensation that occur in distributed metering systems.

References

[1] IEA, Is cooling the future of heating?, (2020).

[2] A. Mugnini, G. Coccia, F. Polonara, A. Arteconi, Potential of District Cooling Systems: A Case Study on Recovering Cold Energy from Liquefied Natural Gas Vaporization, (2019).

[3] L. Canale, M. Dell'Isola, G. Ficco, T. Cholewa, S. Siggelsten, I. Balen, A comprehensive review on heat accounting and cost allocation in residential buildings in EU, Energy Build. 202 (2019) 109398. https://doi.org/10.1016/j.enbuild.2019.109398.

[4] M. Dell'Isola, G. Ficco, F. Arpino, G. Cortellessa, L. Canale, A novel model for the evaluation of heat accounting systemsreliability in residential buildings, Energy Build. 150 (2017) 281–293. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.06.007.

[5] G.Ficco, A.Frattolillo, A.Malengo, G.Puglisi, F.Saba, F.Zuena, Field verification of thermal energy meters through ultrasonic clamp-on master meters. Measurement. 151 (2020) (2017).

[6] T. Cholewa, A. Siuta-Olcha, Long term experimental evaluation of the influence of heat cost allocators on energy consumption in a multifamily building, Energy Build. 104 (2015) 122–130.

[7] L. Canale, M. Dell'Isola, G. Ficco, B. Di Pietra, A. Frattolillo, Estimating the impact of heat accounting on Italian residential energy consumption in different scenarios, Energy Build. 168 (2018). https://doi.org/10.1016/j.enbuild.2018.03.040.

[8] M. Dell'Isola, G. Ficco, L. Canale, A. Frattolillo, I. Bertini, A new heat cost allocation method for social housing, Energy Build. 172 (2018). https://doi.org/10.1016/j.enbuild.2018.05.004.

[9] H. Xiao, Z. Yang, J. Shi, B. Wang, W. Shi, Methods for performance metering of indoor units in variable refrigerant flow systems based on built-in sensors, Appl. Therm. Eng. 196 (2021) 117268.

[10] F. Niu, Z. O'Neill, C. O'Neill, Data-driven based estimation of HVAC energy consumption using an improved Fourier series decomposition in buildings., Build. Simul. 11 (2018) 633–645.

[11] E.W. Lemmon, I.H. Bell, M.L. Huber, M.O. McLinden, NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology, Standard Reference Data Program., Gaithersburg, 2018.

[12] International Organisation for Standardization, ISO/IEC 17043:2010 Conformity assessment — General requirements for proficiency testing, (2010).

[13] JCGM - Joint Committee For Guides In Metrology, JCGM 100:2008 – Evaluation of measurement data – Guide to the expression of uncertainty in measurement., (2008).