

Data Fusion Heat Pump Performance Estimation

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Abstract

The aim of the study was to develop improved measurements on heat pump performance. A model-based approach was combined with data fusion technique to estimate performance of a heat pump. These improved heat pump performance measurements implied fused measurement between direct and indirect measurements of compressor power and condenser load. Developed models of compressor power and condenser load used input data from building energy management system to produce measurements on the heat pump performance. The direct measurements were obtained by using the temperature and pressure measurements, while the indirect measurements were obtained using the electrical signal of the heat pump part load. The results showed a big need for use of different data sources to define real energy performance metrics. Further, the analysis on obtained measurements showed that indirect and fused measurements were more reliable than only direct measurement, particularly for the condenser load. Use of only direct measurements could result in higher estimation of electricity and heating energy consumption than the real consumption is. The analysis of fused measurements on the heat pump performance showed that such improved measurement could enhance heat pump performance verification.

Keywords: heat pump performance, data fusion, direct measurement, indirect measurement

Nomenclature

C	clearance factor, (-)
COP	coefficient of performance, (-)
c_p	specific heat capacity, (kJ/kgK)
d	Moffat distance, (-)

l_w	the length of the moving window, (-)
m	exponent for heat exchanger, (-)
\dot{m}	mass flow rate, (kg/s)
N	revolution speed, (Hz)
p	pressure, (bar)
Δp	pressure difference, (bar)
t	part load of heat pump, (-)
T	temperature, ($^{\circ}\text{C}$)
U	uncertainty, (kW)
UA	the overall heat transfer coefficient, (W/K)
\dot{V}_s	the theoretical compressor volume flow rate, (m^3/s)
\dot{V}	volumetric flow rate, (m^3/s)
\dot{Q}	thermal load, (kW)
\dot{W}	power, (kW)
γ	isentropic exponent, (-)
η	efficiency, (-)
λ	data fusion coefficient, (-)

Subscripts

c	condenser
cd	condensation
d	direct
dis	discharge
ev	evaporation
f	fused
FL	full load
id	indirect
k	current time instant
l	load
$loss$	constant part of the electromechanical power losses

<i>m</i>	manufacturer data
<i>out</i>	outdoor
<i>p</i>	power
<i>R</i>	refrigerant
<i>suc</i>	suction
<i>t</i>	isentropic process
<i>w</i>	mixture of water and glycol
<i>w,in</i>	condenser inlet temperature
<i>w,out</i>	condenser outlet temperature

1. Introduction

Ambitious targets of energy efficiency and zero energy/emission buildings can be achieved only if advanced energy efficiency technologies match expectation; otherwise building energy consumption even can be increased. Therefore, quality control of the complete energy system is essential if CO₂ targets are to be met as pointed out in [1]. To perform a proper quality control of a building, it is necessary to have enough data on building performance. For example, in the study of Parker [2], it was shown that to evaluate real-world potential of zero energy homes in North America, most of the buildings were highly instrumented and monitored. One building was even instrumented with dynamic feedback to occupants. All this means that if we want to achieve confirmed results in energy efficiency, different and reliable sources of measurements on building performances are a high priority.

The research work in Annex 47, Cost-effective Commissioning for Existing and Low Energy Buildings [3], showed a big need for sensor deployment for the purpose of fault detection and diagnosis, improvement in operation, and performance optimization. Further, a new research work in Annex 53, Total Energy Use in Buildings: Analysis and Evaluation Methods [4], has specified as one of task development of measurement techniques for the purpose of estimating real energy use in buildings.

In this study a model-based approach was combined with data fusion technique to estimate performance of a heat pump. Models on heat pump performance were used to produce two types of measurements: direct and indirect. Afterwards, these measurements were combined using data fusion to estimate real performance. The idea to develop this approach came from a

finding in research on lifetime commissioning [5, 6]. Due to poor functional integration, heat pump compressor electrical measuring device was monitoring very low and constant electrical consumption even though heat pump was running. Also, quite higher condenser load was registered. Therefore, reliable information is very important in building operation. There is a potential for maintenance improvement by providing proper information support as shown in [7].

The models on heat pump performance measurements were developed based on available literature references. The direct models on compressor power and condenser load were developed based on [8-11]. The indirect models on compressor power and condenser load were developed based on manufacturer data and relations established in [12]. Manufacturer data were found enough reliable for the purpose of the study because use of them is also recommended by the standard EN 15450 [13]. Both direct and indirect models were calibrated to manufacturer data using least square method, which was suggested for such purposes in [14]. Developed models were supplied with measurement data from building energy management system (BEMS) to produce measurements on the heat pump performance.

Temperature and pressure measurements were used to establish direct measurements on the heat pump performance. Since temperature measurements sometimes suffer from noise, outlier and systematic errors, use of data fusion technique can help to estimate real performance data as shown in [15]. Successful use of data fusion technique for estimation of real cooling load and improvement in chiller sequence control is shown in [15, 16], where a fusion scheme was developed to combine the complementary advantages of a direct and an indirect measurements of the cooling load of chiller plants.

Heat pump models, model calibration algorithm, and data fusion method were developed on MATLAB platform [17].

This paper consists of four parts. The first part gives direct and indirect models on heat pump performance, together with model calibration. To prove the models and define important parameters for data fusion, a sensitivity and uncertainty model analysis was performed. The second part of the paper introduces data fusion method developed for the heat pump performance. The analyzed heat pump and available measurements are introduced in the third part. The results and comparison of three different measurements, direct, indirect and fused, are given in the fourth part of the paper.

2. Heat pump performance estimation

Simulation models of heat pump performance are necessary throughout heat pump life cycle for performance assessment, performance optimization, estimation of energy consumption, and lifetime commissioning. These simulation models enhanced with real measurements from BEMS can give valuable information for improvement in operation and optimization of control. Further, simulation output can be used as a new source of virtual measurement to improve information of a real measurement that might be erroneous. In this study, two steady-state models of the same heat pump performance were developed. Data from manufacturer technical guide and BEMS measurement were combined to estimate heat pump performance, compressor power, and condenser load. The aim with the two models on compressor power and condenser load was to estimate the real heat pump performance. Both models were developed from basic thermodynamic principles and heat transfer relations. The only difference in the models was the input data. The developed models in this study are based on: direct measurement and indirect measurement. The first model is based on the direct measurement, while the second model is based on manufacturer data and electrical signal of the heat pump part load. Finally, these two models are combined into a fused measurement to get a better estimation of the heat pump performance.

2.1. Heat pump performance based on direct measurements

BEMS give the possibility to monitor several measurements related to heat pump, such as, condensation and evaporation temperature, and pressure. These measurements can be used to calculate heat pump performance. The simulation model for heat pump performance based on direct measurements used temperature and pressure measurements.

The direct measurement of the condenser load can be obtained using temperature difference as

$$\dot{Q}_{c,d} = \rho \cdot \dot{V}_w \cdot c_{pw} \cdot (T_{w,out} - T_{w,in}), \quad (1)$$

where data on the mixture of water and glycol flow rates, \dot{V}_w , were obtained by calibrating the model to manufacturer data. Inlet and outlet temperatures of the condenser, $T_{w,in}$ and $T_{w,out}$, were measured with BEMS.

The reason to improve the direct measurement in Eq. (1) with the fusion technique was that temperature measurements can suffer from noise, outlier, and systematic errors as noticed in [15]. An example of water temperature measurement of the condenser outlet temperature, RT 40, and condenser inlet temperature, RT 50, is shown in Figure 1.

Figure 1. Measurements of outlet (RT40) and inlet (RT50) condenser temperature

In the winter period when the heat pump is used to heat the supply water, temperature RT 40 should be higher than RT 50. But due to mentioned difficulties in temperature measurement, it is possible that measurements as in Figure 1 are obtained. Consequently, direct measurement of the condenser load based on the temperature difference can be wrong. Therefore, in our study, the direct measurement was assessed and fused with indirect measurement.

The direct model of the compressor power was developed based on literature resources [8-10]. The compressor power of the isentropic process can be expressed as:

$$\dot{W}_t = \frac{\gamma}{\gamma-1} \cdot \dot{V}_s \cdot \left[1 + C - C \left(\frac{p_{dis}}{p_{suc}} \right)^{\frac{1}{\gamma}} \right] \cdot p_{suc} \cdot \left[\left(\frac{p_{dis}}{p_{suc}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right], \quad (2)$$

where suction and discharge pressures were obtained as:

$$p_{dis} = p_{cd} + \Delta p \quad (3)$$

$$p_{suc} = p_{ev} - \Delta p. \quad (4)$$

Finally, the compressor power can be expressed as:

$$\dot{W}_d = \frac{\dot{W}_t}{\eta} + \dot{W}_{loss}, \quad (5)$$

where \dot{W}_{loss} is the constant part of the electromechanical power losses, and η is the loss factor used to define the electromechanical loss that is proportional to the isentropic compressor power

\dot{W}_i give in Eq. (2). Eqs. (2) to (6) define the compressor power model based on direct measurement. The compressor power model was defined by suction and discharge pressure, which were possible to log from BEMS. In Eqs. (2) to (6) the model parameters, which are theoretical compressor volume flow rate \dot{V}_S , isentropic exponent γ , clearance factor C , pressure drop due to suction and discharge valve Δp , compressor efficiency η , and compressor loss \dot{W}_{loss} , were obtained by calibrating the model to manufacturer data. Model calibration will be introduced in Section 2.3. Pressure increase and decrease due to suction and discharge valve, Δp , might not have the same value, but due to model simplification and use of fewer model parameters, it was assumed to be the same value as in [9].

2.2. Heat pump performance based on indirect measurements

The idea with this model was to utilize data from the manufacturer technical guide *and* BEMS measurement. This indirect measurement only uses electrical signal of the heat pump part load and combine this with the manufacturer data. The manufacturer provides tabular data for the condenser load and compressor power based on outdoor and water temperatures as given in Table 1 and 2. An example of the electrical signal measurement is shown in Figure 2. This signal gives information on heat pump part load in terms of fraction of full load as given in Eq. (6). Electrical signals in Figure 2 present part load of heat pump circuits shown in Figure 5. Combining manufacturer data for the full load, as defined in Table 1 and 2, and compressor signal, which tells what the part load is, it is possible to calculate compressor power and condenser load.

Table 1. Manufacturer data for condenser load of the heat pump

Table 2. Manufacturer data for compressor power of the heat pump

Data from Table 2 and electrical signal were used for the indirect compressor power measurement, while data from Table 1 and electrical signal were used for the indirect condenser load measurement.

Figure 2. Electrical signal of the heat pump part load

Before the indirect model of the heat pump is introduced, a non-dimensional relation that is equal to the part load is defined as in [8]:

$$t = \frac{N}{N_{FL}} = \frac{\dot{m}_R}{\dot{m}_{RFL}} = \frac{\dot{W}}{\dot{W}_{FL}}. \quad (6)$$

t is the part load that can be measured in BEMS.

Next, a non-dimensional relation is relevant for calculation of the condenser load at part load. This non-dimensional relation defines the overall heat transfer coefficient at part load as in [12]:

$$\frac{UA_c}{UA_{c,FL}} = \left(\frac{\dot{m}_R}{\dot{m}_{RFL}} \right)^m = t^m. \quad (7)$$

The exponent m in Eq. (7) cannot be obtained by using the calibration method as for the other parameters, since the calibration was done for full load, and this exponent is relevant for part load. Therefore, this exponent was assumed to be 0.8 as in references [11, 12].

Finally, using the two non-dimensional relations, Eqs. (6) and (7), and manufacturer technical data, it was possible to indirectly estimate the compressor power and the condenser load. By using non-dimensional relation in Eq. (6), it was possible to calculate compressor power at part load as:

$$\dot{W}_{id} = t \cdot \dot{W}_{FL}(T_{out}, T_{w,out}) \quad (8)$$

where $\dot{W}_{FL}(T_{out}, T_{w,out})$ is the compressor power at full load given, as in Table 2.

The indirect model of the condenser load can be expressed as:

$$\dot{Q}_{c,id} = \frac{1 - \exp\left(-\frac{UA_{cd,FL}}{\dot{m}_w \cdot c_{pw}} \cdot t^m\right)}{1 - \exp\left(-\frac{UA_{cd,FL}}{\dot{m}_w \cdot c_{pw}}\right)} \cdot \dot{Q}_{cd,FL}(T_{out}, T_{w,out}), \quad (9)$$

where $\dot{Q}_{FL}(T_{out}, T_{w,out})$ is the condenser load at full load given, as in Table 1. UA of the heat exchanger is an additional model parameter and was obtained by calibrating the model to the manufacturer data.

2.3. Model calibration

Model calibration was done by using manufacturer data as given in Table 1 and 2. The aim was to find model parameters that can fit as good as possible to each operating point. The model calibration process was performed using the following objective function:

$$\min \sum_{i=1}^N \left[\left(\frac{\dot{W}_{m,i} - \dot{W}_{d,i}}{\dot{W}_{m,i}} \right)^2 + \left(\frac{\dot{Q}_{cm,i} - \dot{Q}_{c,id,i}}{\dot{Q}_{cm,i}} \right)^2 \right] \quad (10)$$

A similar method for model calibration was shown in [8, 9]. The variable of the objective function in Eq. (10) are model parameters theoretical compressor volume flow rate \dot{V}_s , isentropic exponent γ , clearance factor C , pressure drop due to suction and discharge valve Δp , compressor efficiency η , compressor loss \dot{W}_{loss} , the overall heat transfer coefficient of the heat exchanger UA , and mixture of water and glycol volumetric flow rate \dot{V}_w . The upper and lower boundary values of the model parameters were assumed based on the design and balancing data, and literature references from [8-10]. The model calibration was necessary for direct compressor model, and direct and indirect condenser load models. Eq. (8) shows that the indirect compressor power model does not have any parameter that need to be adjusted to the manufacturer data. The optimization results of Eq. (10) expressed in terms of model parameters are given in Table 3. Table 3 gives an overview of model parameters and the application for each parameter.

Table 3. Heat pump model parameters

2.4. Model uncertainty and sensitivity

Information on model uncertainty was important for the fusion method. The model uncertainty shows how much the model outputs were different from the manufacturer data. To prove the introduced heat pump models, sensitivity analysis was performed for a range of

operating points. This sensitivity analysis had aim to show which parameters could influence model output mostly. In addition, the sensitivity analysis can be used to determine approximate values of the model parameters without using optimization to calibrate the models.

Upper and lower parameter bounds of the optimization problem in Eq. (10) were adopted based on literature sources and manufacturer data [8-10]. However, some parameters can influence model outputs more. Even though the model parameters were obtained using optimization, they are not exact. Therefore, it is beneficial to present which parameters influence the model outputs the most. The compressor direct model and the condenser load indirect model were tested for the range of the parameters. Figure 3 displays influence of the change in isentropic exponent, γ , on the direct compressor model for different operating points. The subfigures in Figure 3 are displayed for different condensation pressures, while the axes represent the ratio between condensation and evaporation pressure. The results in Figure 3 show that the higher the isentropic exponent, the higher the compressor power. A summary of the isentropic exponent influence on the direct compressor model is given in Table 4.

Figure 3. Compressor model sensitivity on change in isentropic exponent

Figure 4 displays the influence of a change in the theoretical compressor volume flow rate on the direct compressor model for different operating points. This figure consists of subfigures for different condensation pressure.

Figure 4. Compressor model sensitivity on change in volumetric flow rate

The range of theoretical compressor volume was chosen broad for the purpose of testing the influence of compressor volume. The results in Figure 4 show that the higher the theoretical compressor volume flow rate, the higher the compressor power. A summary of the compressor volume influence on the direct compressor model is given in Table 4.

The entire sensitivity analysis for all the direct compressor model parameters is given in Table 4. The reference value for the compressor power for this sensitivity analysis was the calibrated model value. Sensitivity analysis was not performed for suction and discharge valve pressure drop, because it was possible to measure these suction and discharge pressure directly in BEMS. In Eq. (2), there was a need to introduce pressure drop due to suction and discharge valve,

because manufacturer data in Table 2 were given for the condensation and evaporation temperatures. Based on temperatures the pressures could be calculated. The suction and discharge pressures were obtained directly from the BEMS measurement and hence, it was not relevant for study to analyze the influence of these pressure drops.

Table 4. Direct compressor model sensitivity

In Table 4, clearance factor, C has literally wide range of the parameter values. The reason to choose this wide range was lack of big variance in literature. Therefore, the compressor model was tested for different values of the clearance factor that were chosen as a percentage of the theoretical compressor volume. However, regardless of this wide range, the clearance factor does not have significant influence on the compressor power. The results in Table 4 show that the following parameters have the largest influence on the direct compressor model: theoretical compressor volume flow rate, isentropic exponent, and compressor efficiency.

The sensitivity analysis of the indirect condenser model is given in Table 5. Similarly as in Table 4, the referent value of the condenser load was the calibrated model value. The results of the condenser model sensitivity are given for different values of the condensation pressure.

Table 5. Indirect condenser model sensitivity

Results on the sensitivity analysis in Table 5 show that a change in the overall heat transfer coefficient has a more significant influence on the indirect condenser model than the mixture of water and glycol volumetric flow rate. Data on the overall heat transfer coefficient of the condenser could be obtained from the manufacturer or calculated based on commissioning data. Therefore, a suitable range for this parameter could readily be found. Data on the mixture of water and glycol volumetric flow rate could be obtained from assembling drawings, circulating pump data, and balancing data. Even though these data can be different in practice, they are still helpful to give some approximate value for estimation.

The uncertainty of the heat pump models was obtained by comparing direct and indirect models, and manufacturer data. Actually, the value of the model uncertainty was obtained as result of Eq. (10). The absolute average error of the direct compressor model was 7.6 %. The absolute error of the direct condenser load model was 7 %, while the absolute error of the indirect

condenser model was 6.3 %. Therefore, for the purpose of the data fusion method, direct compressor power uncertainty was assumed to be 7.6 % and the direct condenser load uncertainty to be 7 %. Regarding indirect model of the compressor power, there were no data on the electrical signal quality. The indirect compressor model used electrical signal as input parameter, so a value of 5 % for uncertainty associated to the indirect compressor model was assumed. For uncertainty associated with the indirect condenser model, a value of 6.3 % was assumed. These data on uncertainty, expressed as percentage, were multiplied with the real measurement to obtain data on the uncertainty index for data fusion.

3. Performance estimation based on data fusion

Direct and indirect measurements of the compressor power and the condenser load were available but with uncertainties. Data fusion was therefore used to improve the reliability of the estimations of the compressor power and the condenser load by reducing uncertainties associated with the measurements. The fusion algorithm follows the steps of removing outliers in the direct/indirect measurements and combining the measurements to produce fused measurements.

3.1 Detection and removal of outliers

Since outliers have a significant influence on the fusion, it was necessary to remove outliers before fusing the direct and indirect measurements. Outliers were detected and removed according to consistency between the direct and indirect measurements. Given a direct measurement x_d and an indirect measurement x_{id} and the associated uncertainty indices U_d , U_{id} , the Moffat distance between the two measurements was used as an indicator of consistency [18]. The Moffat distance is defined as

$$d_{di} = \frac{|x_d - x_{id}|}{\sqrt{U_d + U_{id}}}. \quad (11)$$

The algorithm of removing outliers follows the procedure illustrated by Duta and Henry [19]. A moving window which is used to store previous data is necessary in this algorithm. The moving window had two columns, which stored direct and indirect measurements separately. The length of the moving window is denoted as l_w . The algorithms of removing outliers and updating

the moving window are described below. Both algorithms were applied to the direct and indirect measurements of the compressor power and the condenser load.

Algorithm of outlier removal

Step 1: Initialize a threshold d and a moving window;

Step 2: For each pair of direct and indirect measurements, calculate the Moffatt distance d

Step 2.1: if $d_{di} \leq 1$; then no outlier is detected;

Step 2.2: if $1 < d_{di} < d$; then no outlier is detected. Calculate the differences between the current direct/indirect measurement and the average of the direct/indirect measurements stored in a moving window, respectively. Find the maximum, and update the corresponding uncertainty index by timing d_{di} .

Step 2.3: if $d_{di} \geq d$, then an outlier is detected. Calculate the differences between the current direct/indirect measurement and the average of the direct/indirect measurements stored in the moving window, respectively, and find the maximum. The outlier is the one with the maximum difference.

Algorithm of moving window update

For each pair of direct and indirect measurements, if there is no outlier found, then replace the data in the i^{th} row of the moving window with the data stored in the $(i-1)^{\text{th}}$ row from $i = l_w$ to 1; and current measurements are placed into the 1^{st} row; otherwise no update is taken.

3.2 Data fusion algorithm for compressor power measurement

Since the algorithm of removing outliers may modify the uncertainty indices (at step 2.2), the uncertainty indices $U_{p,d}$ and $U_{p,id}$ subsequent of removing outliers were denoted as $U_{p,d,n}$ and $U_{p,id,n}$. According to reference [20], the combined best estimate (CBE) of the compressor power is given by

$$\dot{W}_{f,k} = \lambda_1 \cdot \dot{W}_{d,k} + \lambda_2 \cdot \dot{W}_{id,k} . \quad (12)$$

Where the coefficient parameters are defined by

$$\lambda_{p,1} = \frac{U_{p,id,n}^2}{U_{p,d,n}^2 + U_{p,id,n}^2}, \lambda_{p,2} = \frac{U_{p,d,n}^2}{U_{p,d,n}^2 + U_{p,id,n}^2} \quad (13)$$

The fused uncertainty index becomes

$$U_{p,f} = 1 / \sqrt{\frac{1}{U_{p,d,n}^2} + \frac{1}{U_{p,id,n}^2}} \quad (14)$$

It can be shown that the fused uncertainty index is smaller than both $U_{p,d}$ and $U_{p,id}$. It should be noted that when a measurement is detected as an outlier, the other one, which is without outlier, is then used as the fused measurement and the associated uncertainty index as the fused uncertainty index.

3.3 Data fusion algorithm for condenser load measurement

Similarly, when using $U_{l,d,n}$ and $U_{l,id,n}$ to denote the uncertainties associated with the direct/indirect measurements of the condenser load after removing outliers, the combined best estimate (CBE) of the condenser load is

$$Q_{f,k} = \lambda_{l,1} \cdot Q_{d,k} + \lambda_{l,2} \cdot Q_{id,k} \quad (15)$$

where the coefficient parameters are

$$\lambda_{l,1} = \frac{U_{l,id,n}^2}{U_{l,d,n}^2 + U_{l,id,n}^2}, \lambda_{l,2} = \frac{U_{l,d,n}^2}{U_{l,d,n}^2 + U_{l,id,n}^2} \quad (16)$$

The fused uncertainty index is

$$U_{l,f} = 1 / \sqrt{\frac{1}{U_{l,d,n}^2} + \frac{1}{U_{l,id,n}^2}} \quad (17)$$

Once again, please note that once a measurement is detected as an outlier, the other measurement is then used as the fused measurement and the associated uncertainty index as the fused uncertainty index.

3.4 Application issues

Both the direct and indirect measurements contribute to the fused measurements. However, the fusion formulas Eqs. (12) and (15) show that when a measurement is associated with a larger uncertainty index, its contribution is smaller. Therefore, uncertainty analysis becomes important for the fusion results. Uncertainty analysis can be done during commissioning, when data are available. This is shown in Section 2.4.

4. Case study

The developed approach for direct, indirect, and fused measurements of the heat pump performance was tested on the heat pump displayed in Figure 5. This heat pump is installed in an office building in Trondheim, Norway. The heat pump supplies eight coils in eight air handling units and works as heat pump in winter and as cooling plant in summer. The heat pump has six compressors connected into two circuits and COP=3.22. The working fluid is R410A. The circulating pump in the secondary side of the condenser is a constant flow circulating pump. Manufacturer data on condenser load and compressor power for this heat pump are given in Table 1 and 2, respectively. The heat pump is connected to the BEMS and the following data were possible to measure: inlet and outlet temperatures of the condenser, suction and discharge pressures, electrical signals of the circuit part load, electrical signal of the circulating pump (on/off), and outdoor air temperature.

Figure 5. Heat pump used for case study

Some of the measurements of the heat pump were shown in the previous text. Temperature measurements of the sensors RT 40 and RT 50 are displayed in Figure 1. Electrical signals of the part load on Circuits 1 and 2 are displayed in Figure 2.

The direct and indirect measurements of the heat pump performance in Figure 5 were modeled using Eqs. (1) to (9). Since the heat pump has six compressors connected into two circuits, two larger compressors were modeled using Eqs. (2) and (5). A larger compressor was modeled for each circuit instead of three parallel compressors. This means that two compressors with the same parameters were developed to simulate two compressor circuits. This simplification was done due to reduce the number of model parameters. Available manufacturer data, as given in Table 1 and 2, give 30 operating points. The developed model was calibrated using Eq. (10) and has eight parameters. In this way, the number of operating points or fitted data was higher than the number of model parameters, and the problem was straight-forward to solve as mentioned in [14]. In the case that each compressor has its own parameters, the calibration problem will have 38 parameters, and the optimization problem becomes indefinite.

5. Results

Results of heat pump performance estimation show the performance measurements obtained using different methods, specifically direct, indirect, and fused measurements. For each of these methods, uncertainty associated with the measurement was calculated too. Consequently, using this additional information on the measurement uncertainty, it was possible to understand quality and reliability of each measurement. Results on the heat pump performance measurement are presented by comparing direct and indirect measurements with the fused measurements. The aim of this comparison is to show the benefit of using several measurements in the performance estimation instead of using only one. In addition, usefulness of the fused measurement is also discussed.

Firstly, direct and indirect measurements on the heat pump performance, condenser load and compressor power are displayed in Figure 6. Outdoor air temperature is also displayed in the lower part of Figure 6. The heat pump performance measurements in Figure 6 were the starting point for this study.

Figure 6. Heat pump performance with direct and indirect measurements. The lowest subfigure displays outdoor temperature.

When outdoor air temperature is under $-12\text{ }^{\circ}\text{C}$, the heat pump is off. The direct measurement of the condenser load, the blue line with squares in the upper part of Figure 6, shows a certain heating load on the condenser. The indirect measurement of the condenser load, the purple line in the upper part of Figure 6, shows no heating load of the condenser when the outdoor air temperature is under $-12\text{ }^{\circ}\text{C}$. This difference occurred because the circulating pump is always on as a measure for freezing protection, and therefore a small temperature difference can give a certain heating load. Results in the upper part of Figure 6 show that use of only the temperature difference to estimate the heat pump performance can be misleading. The direct and indirect measurements of the compressor power, displayed in the middle part on Figure 6, show good agreement. The compressor power obtained by the direct measurement is very low when the outdoor air temperature is under $-12\text{ }^{\circ}\text{C}$, and this measurement can be treated as acceptable.

Direct and fused measurements of the compressor power and condenser load are displayed in Figure 7 and 8, respectively. In both figures associated uncertainties with the measurements are given.

Figure 7. Direct and fused measurement of the compressor power

Results in Figure 7 show good agreement between fused and direct measurement of the compressor power. The fused measurement is free of outliers, while there are several outliers in the direct measurement due to faults in the pressure measurement. The uncertainty associated with the compressor power fused measurement, the lower part in Figure 7, has stable and low values, while uncertainty associated to the direct measurement, the middle part in Figure 7, have several high values.

Figure 8. Direct and fused measurement of the condenser load

The upper part in Figure 8 gives comparison between direct and fused measurement on the condenser load. The red line in the upper part in Figure 8 represents an improved measurement compared to the direct, because it is free of outliers and condenser load is zero when the heat pump is off. Information on the associated measurement uncertainties, the middle and lower part in Figure 8 contributes to this fact by showing that the uncertainty of the direct

measurement, the middle part in Figure 8, has almost four times higher values than the uncertainty of the fused measurement.

Indirect and fused measurements of the compressor power and condenser load are displayed in Figure 9 and 10, respectively. Since the electrical signals without outliers were used to produce indirect measurements, the indirect measurements on the heat pump performance are almost without outliers as shown in Figure 9 and 10. In the process of removing outliers with a moving window, measurements that do not satisfy the Moffat distance were removed. Since the indirect measurements were mostly without outliers, they were used to obtain fused measurements. This is reason that the profiles of the indirect and fused measurement are quite similar in Figure 9 and 10.

Figure 9. Indirect and fused measurement of the compressor power

Figure 10. Indirect and fused measurement of the condenser load

The uncertainty associated with the indirect measurement of compressor power, the middle part in Figure 9, and the uncertainty associated with the fused measurement, the lower part in Figure 9, have quite similar values. The used uncertainty for the direct measurement on the compressor power was 7.6 %, and 5 % for the indirect measurement. Due to similar values between direct and indirect measurements of the compressor power, a high quality and reliable fused measurement was achieved. Condenser load, the upper part in Figure 10, obtained using indirect and fused measurements is zero when outdoor air temperature is under -12 °C. This result corresponds better to the indirect and fused measurements of the compressor power, the upper part in Figure 9. In both of these figures, when the compressor power is zero, the condenser load is zero too. Such result is more reliable than the measurement obtained using only direct measurement of the condenser load.

A summary of the uncertainties associated with each measurement on heat pump performance is given in Table 6. The aim of this data summary is to show the approximate magnitude of the measurement faults.

Table 6. Uncertainty limits (kW) of different measurements of heat pump performance

Results in Table 6 show that fused and indirect measurements are more reliable than only direct measurement, because the uncertainties associated with the fused and indirect measurements are lower than for the direct measurements. Practically, if only the direct measurement would be used for the compressor power estimation, it could result in about 10 % higher electricity consumption than the real electricity consumption is. Further if only direct measurement would be used to estimate heating energy from the heat pump condenser, 27 % higher heating energy consumption would be obtained. Results in Table 6 confirm the statements in Sections 3.2 and 3.2 that fused uncertainty index is the smallest, i.e., the fused measurement gave the best estimation.

Finally, improved measurements on the heat pump performance are displayed in Figure 11. Figure 11 was obtained after removing outliers and data fusing the measurements in Figure 6. Such improved measurements can be used for further analysis and energy consumption estimation.

Figure 11. Heat pump performance fused measurements and outdoor temperature

The fused measurement of the condenser load, the upper part in Figure 11, corresponds well to the fused measurement of the compressor power, the middle part in Figure 11. This correspondence can be noticed through the following:

- when the compressor is off, the condenser load is zero,
- profiles of the condenser load and the compressor power are quite similar, where the ratio between the condenser load and compressor power is about three, which correspond well to $COP=3.22$ given by the heat pump manufacturer.

The above findings show that such improved measurement of the heat pump performance could enhance heat pump performance verification.

6. Conclusions

The study presents an improved method for heat pump performance estimation. This improved method is based on merging direct and indirect measurements into a fused measurement. The direct and indirect measurements of the heat pump performance were obtained using models, which used BEMS measurements as input data. The heat pump model parameters

were obtained by calibrating model to the manufacturer data. Developed data fusion approach removes outliers and calculated uncertainty associated with the observed measurement.

Model uncertainties were defined as input data to the data fusion method. Since heat pump model parameters were based on the manufacturer and balancing data, a brief discussion on model parameters was also given. The results showed that indirect and fused measurements were more reliable than only direct measurement. Since the fused uncertainty index was the smallest of the uncertainty indices, the fused measurement gave the best estimation. The direct measurements of the condenser load had many outliers due to outliers in the temperature measurements. The direct and indirect measurements of the compressor power showed good agreement. In addition, the fusion method combined best of them. The practical meaning of the study was to show the need for different data sources to define real energy performance metrics. As results showed, use of only the direct measurement could result in higher estimation of electricity and heating energy consumption than the real consumption is. Further, the results showed that such improved measurements of the heat pump performance could enhance heat pump performance verification.

Future work should provide detailed data on uncertainty in building energy performance, and should include use of additional information to make stronger relationships between system performance metrics. For example, use of COP as an additional measurement, to be included into the fused measurement.

Acknowledgement

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Table 1. Manufacturer data for condenser load of the heat pump

Leaving water temperature, $T_{w,out}$ (°C)	Ambient air temperature, T_{out} (°C)					
	-5	-3	0	5	7	10
30	329.7	347.0	375.0	424.1	445.7	480.1
35	325.4	345.7	372.8	419.8	440.5	473.7
40	321.5	342.2	371.1	415.9	435.7	467.2
45	318.1	338.3	366.8	412.5	431.0	461.2
50	0.0	0.0	362.9	410.3	427.6	455.6

Table 1. Manufacturer data for compressor power of the heat pump

Leaving water temperature, $T_{w,out}$ (°C)	Ambient air temperature, T_{out} (°C)					
	-5	-3	0	5	7	10
30	93.1	93.4	93.7	95	95.7	96.6
35	109.5	104.5	104.8	106.1	106.8	107.7
40	122.7	117.1	117.5	118.9	119.4	120.5
45	138	131.6	132.1	133.3	134	134.9
50	0.0	0.0	149.4	150.2	150.8	151.6

Table 1. Heat pump model parameters

Parameter	Unit	Value	Application
γ	-	1.3	Direct model
\dot{V}_s	m^3/s	0.0373	Direct model
C	-	0.001	Direct model
Δp	bar	0.15	Direct model
η	-	0.837	Direct model
W_{loss}	W	1001.377	Direct model
\dot{V}_w	m^3/h	88	Direct/Indirect model
UA	W/K	19183.906	Indirect model

Table 1. Direct compressor model sensitivity

Parameter name	Unit	Range	Condensation pressure, p_{cd} (bar)	Change in compressor power (%)
Isentropic exponent, γ	-	1.05 – 1.3	30.45	17.76
			34.08	19.11
			38.03	20.44
			42.32	21.77
			45.84	21.34
Theoretical compressor volume flow rate, \dot{V}_s	m^3/s	0.02 – 0.07	30.45	241.20
			34.08	241.83
			38.03	242.37
			42.32	242.85
			45.84	243.50
Clearance factor, C	-	0.0001 – 0.02	30.45	-4.26
			34.08	-4.80
			38.03	-5.37
			42.32	-5.97
			45.84	-5.71
Efficiency, η	-	0.6 – 0.9	30.45	-32.86
			34.08	-32.90
			38.03	-32.92
			42.32	-32.95
			45.84	-32.99
Compressor losses, W_{loss}	W	0 - 2000	30.45	3.96
			34.08	3.67
			38.03	3.42
			42.32	3.20
			45.84	2.90

Table 1. Indirect condenser model sensitivity

Parameter name	Unit	Range	Condensation pressure, p_{cd} (bar)	Change in condenser load (%)
Overall heat transfer coefficient, UA	W/K	15 000 – 25 000	30.45	58.45
			34.08	58.45
			38.03	58.45
			42.32	58.45
			45.84	58.45
Water and glycol volumetric flow rate, \dot{V}_w	m ³ /h	60 – 120	30.45	-1.23
			34.08	-1.23
			38.03	-1.26
			42.32	-1.57
			45.84	-0.80

Table 1. Uncertainty limits (kW) of different measurements of heat pump performance

	Compressor power			Condenser load		
	Direct	Indirect	Fused	Direct	Indirect	Fused
Min	-22.23	0.00	0.00	-16.10	0.00	0.00
Max	17.80	3.99	3.78	69.16	13.53	13.53

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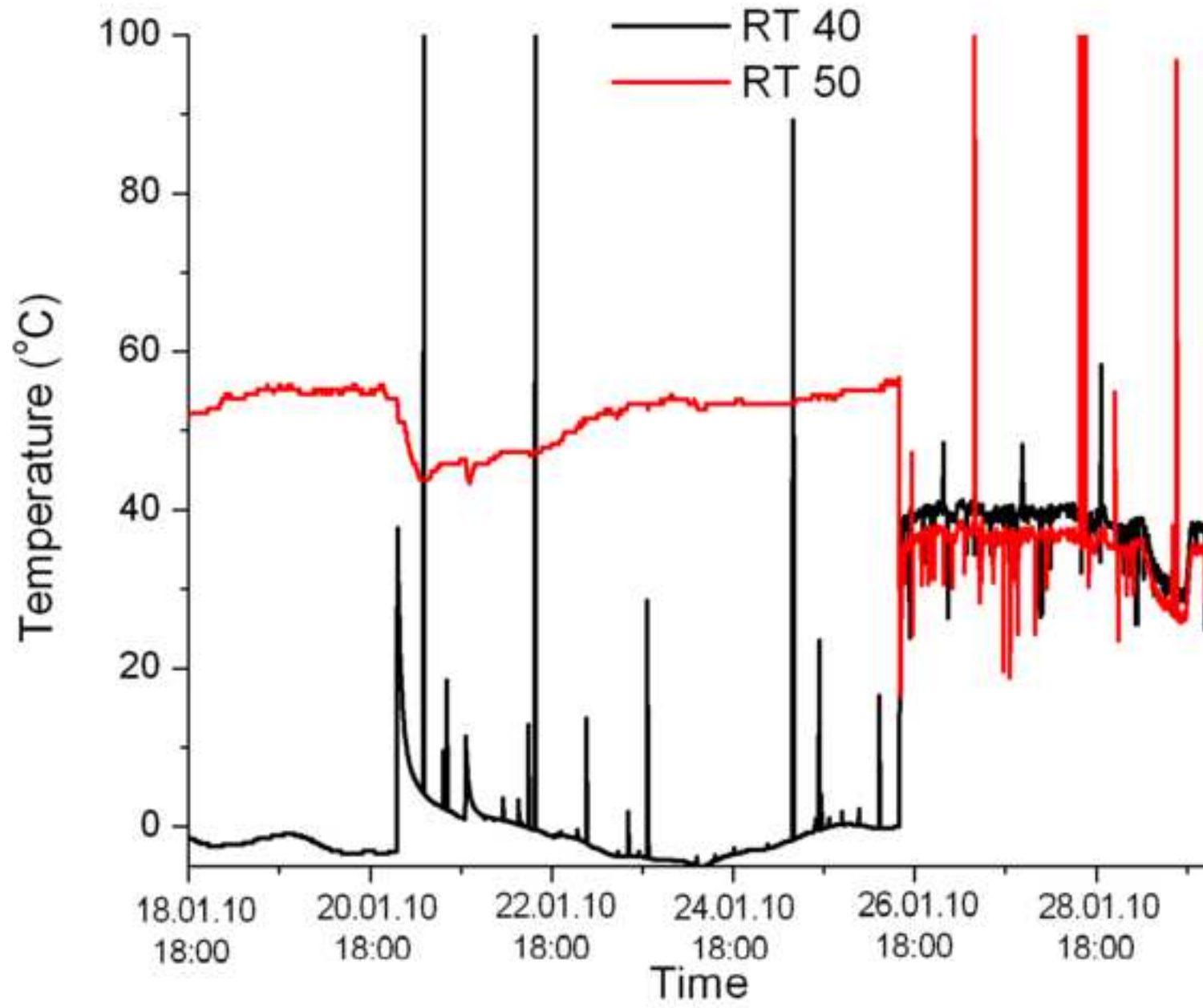


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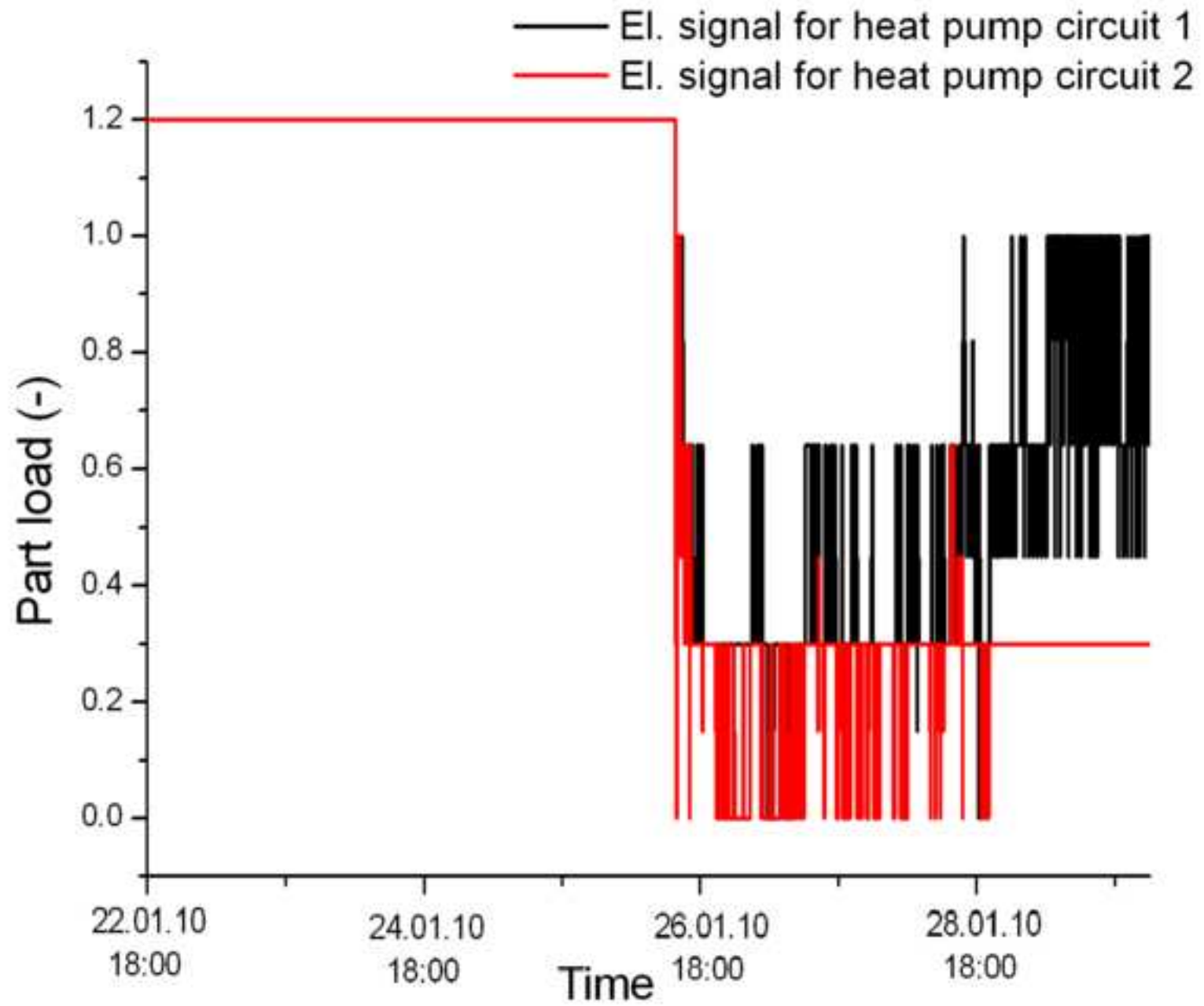


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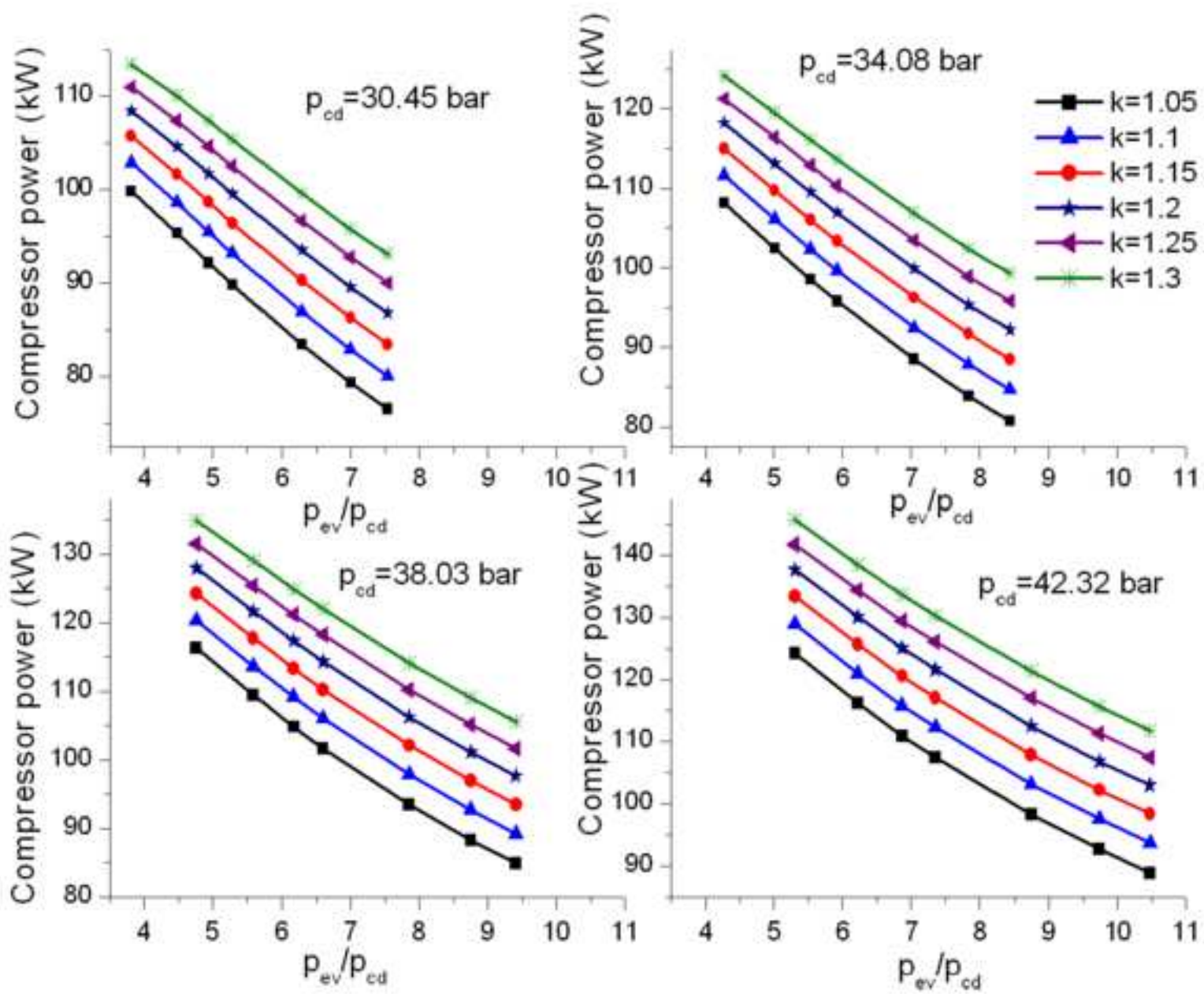


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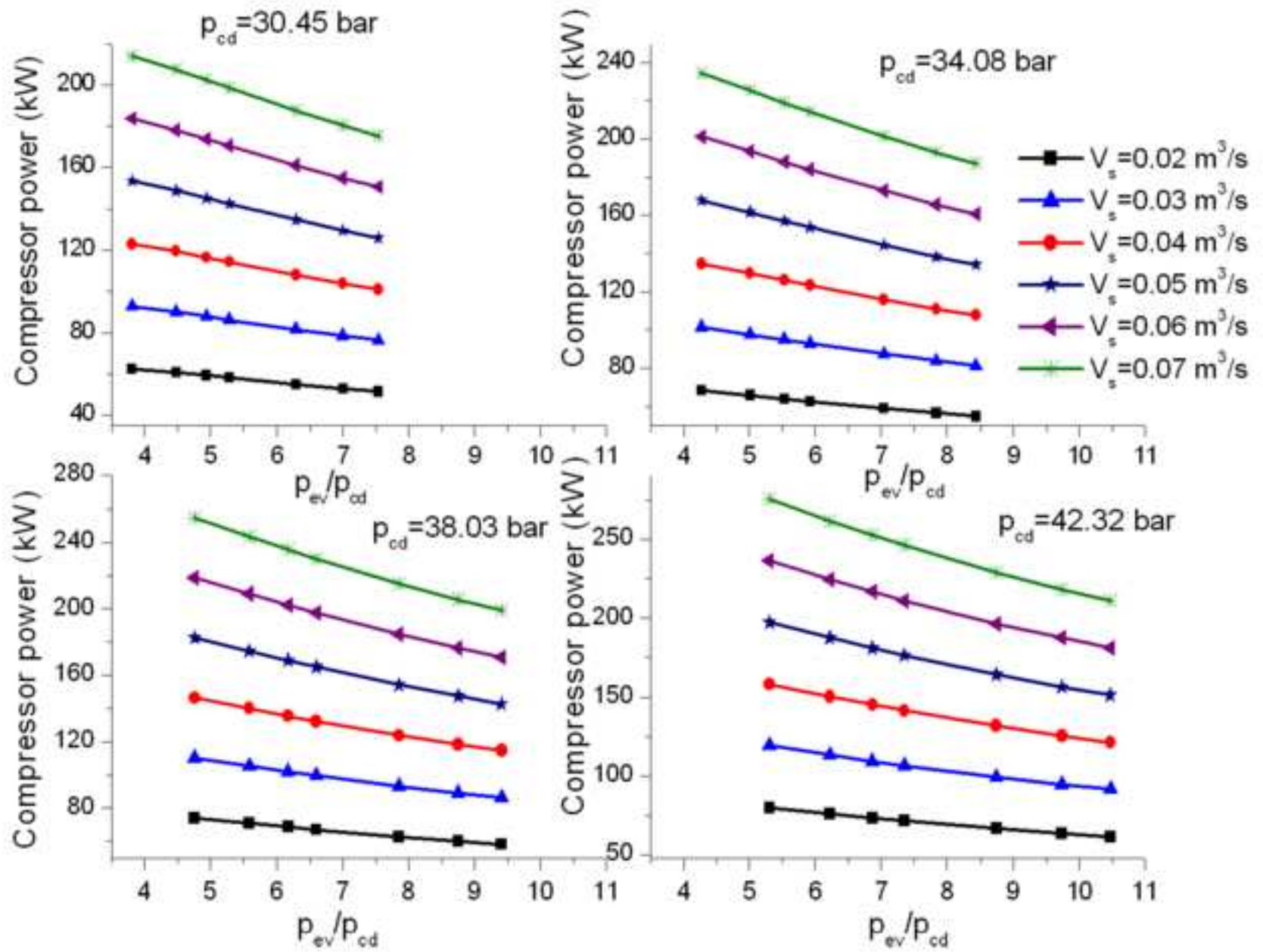


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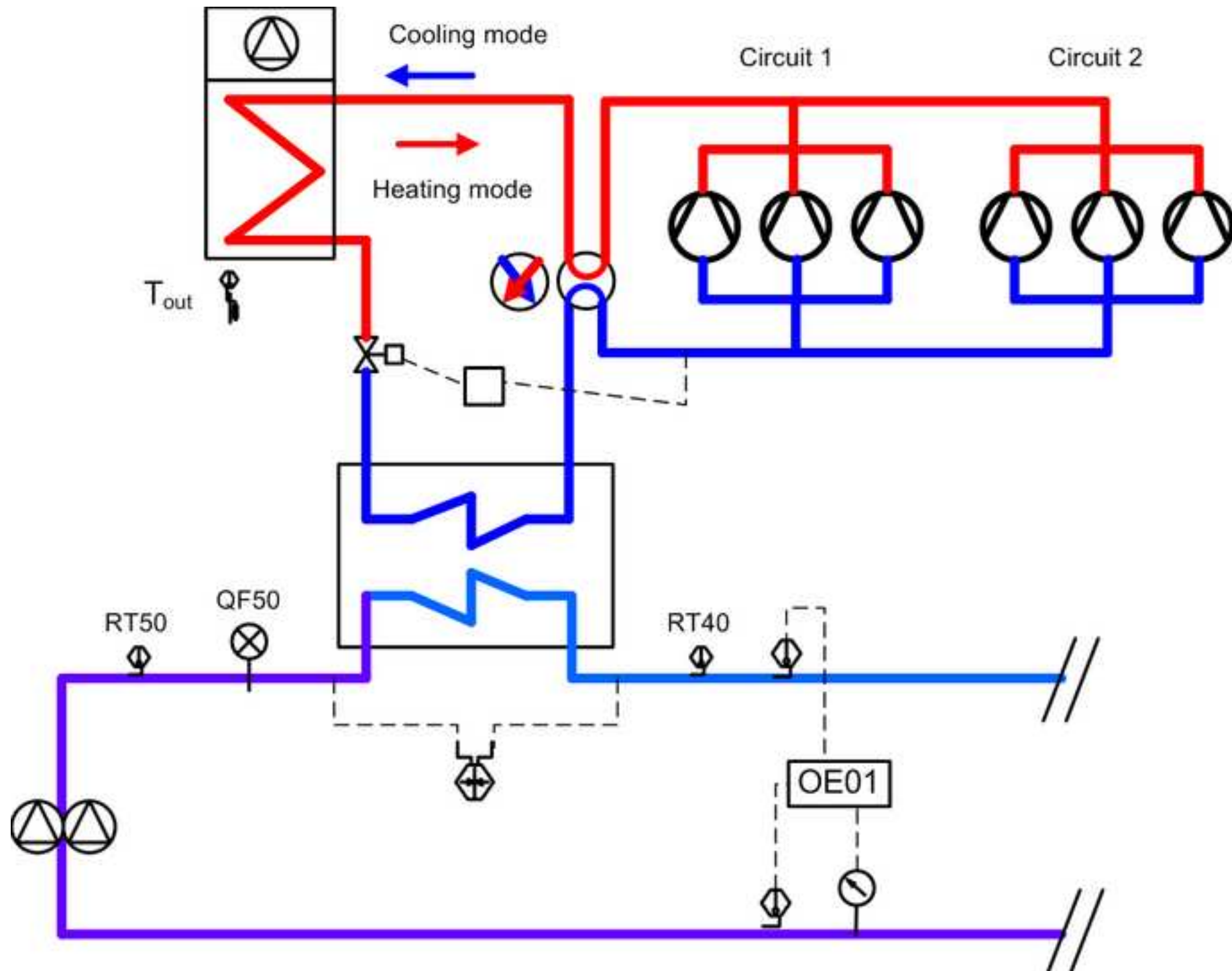


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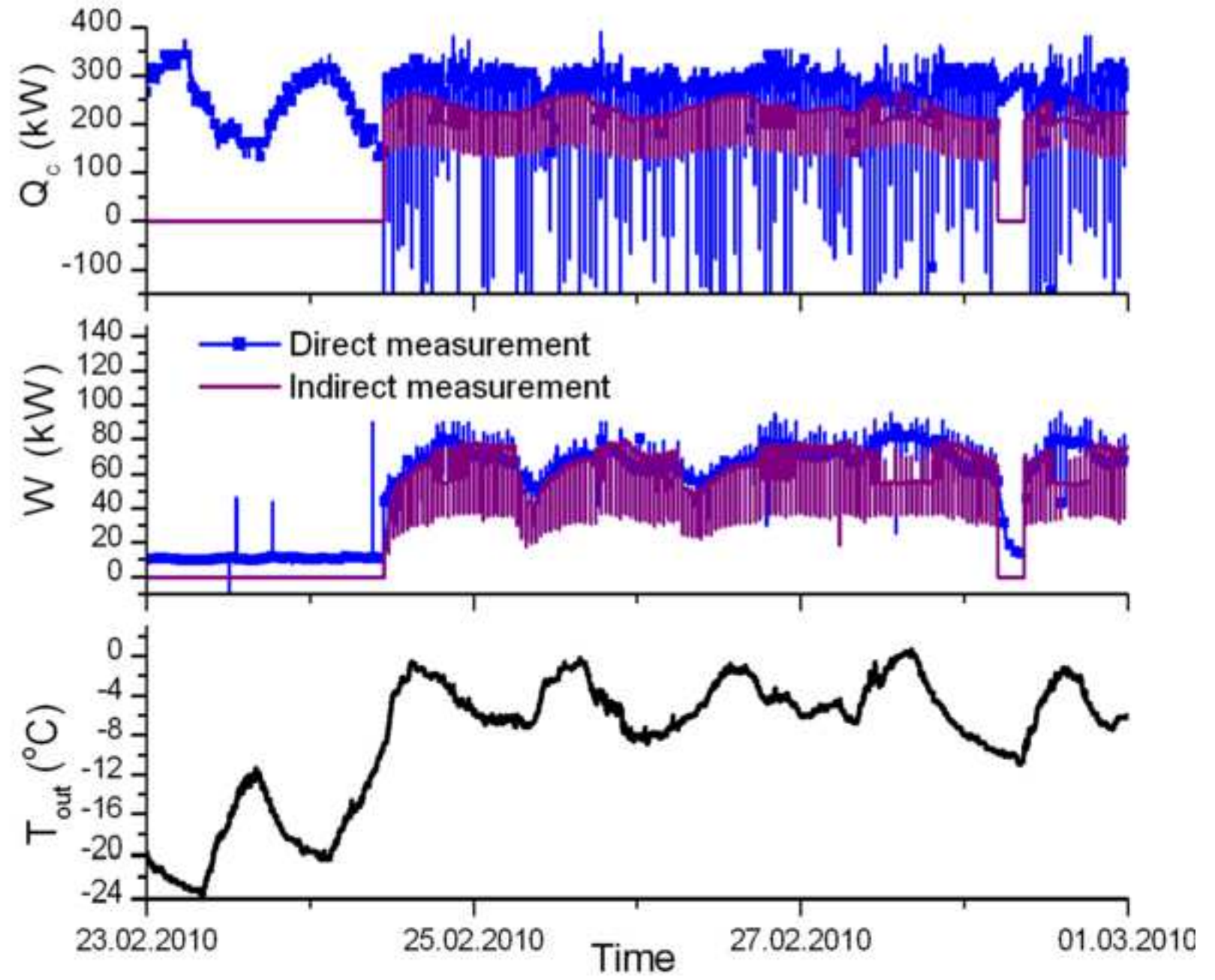


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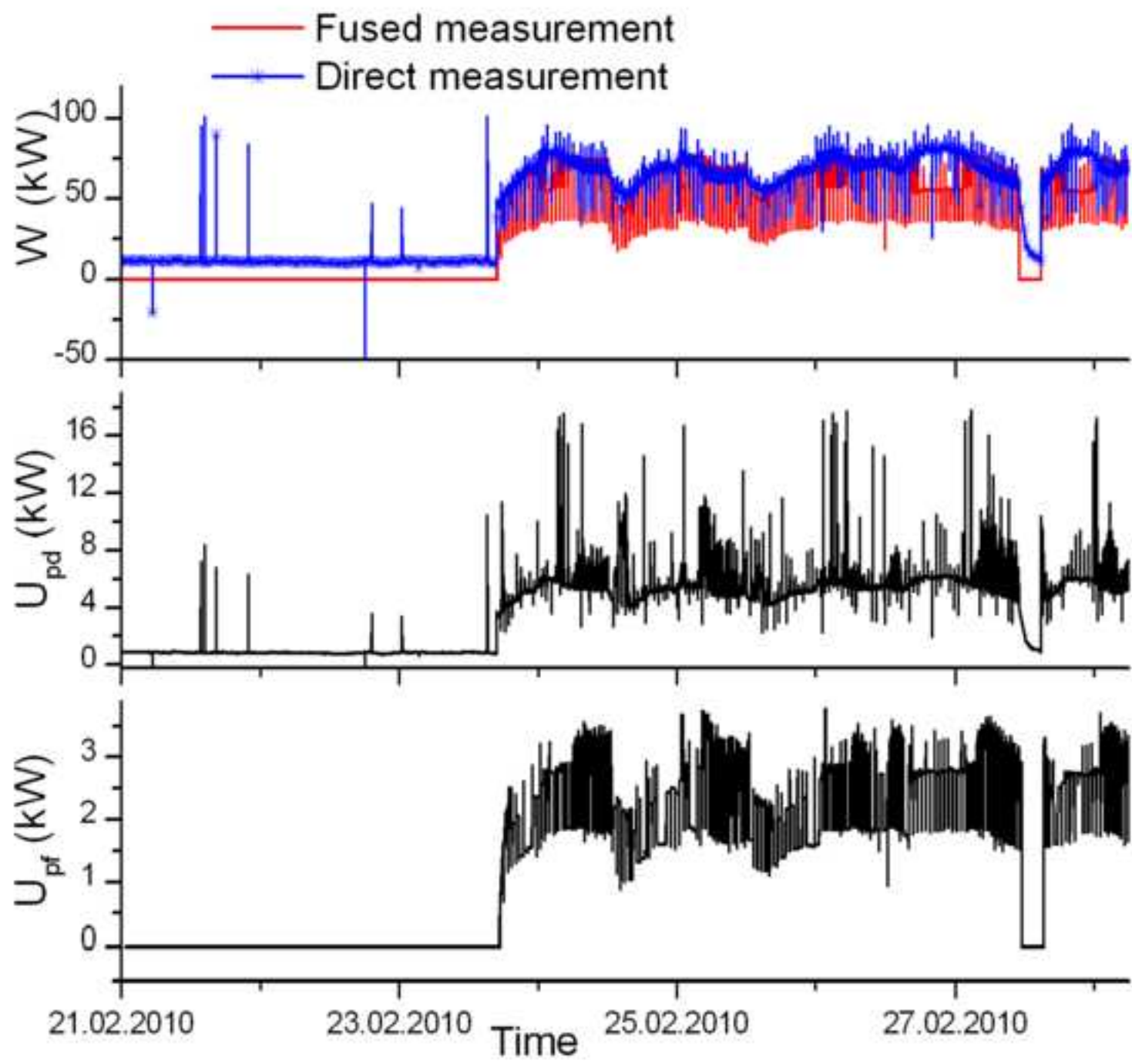


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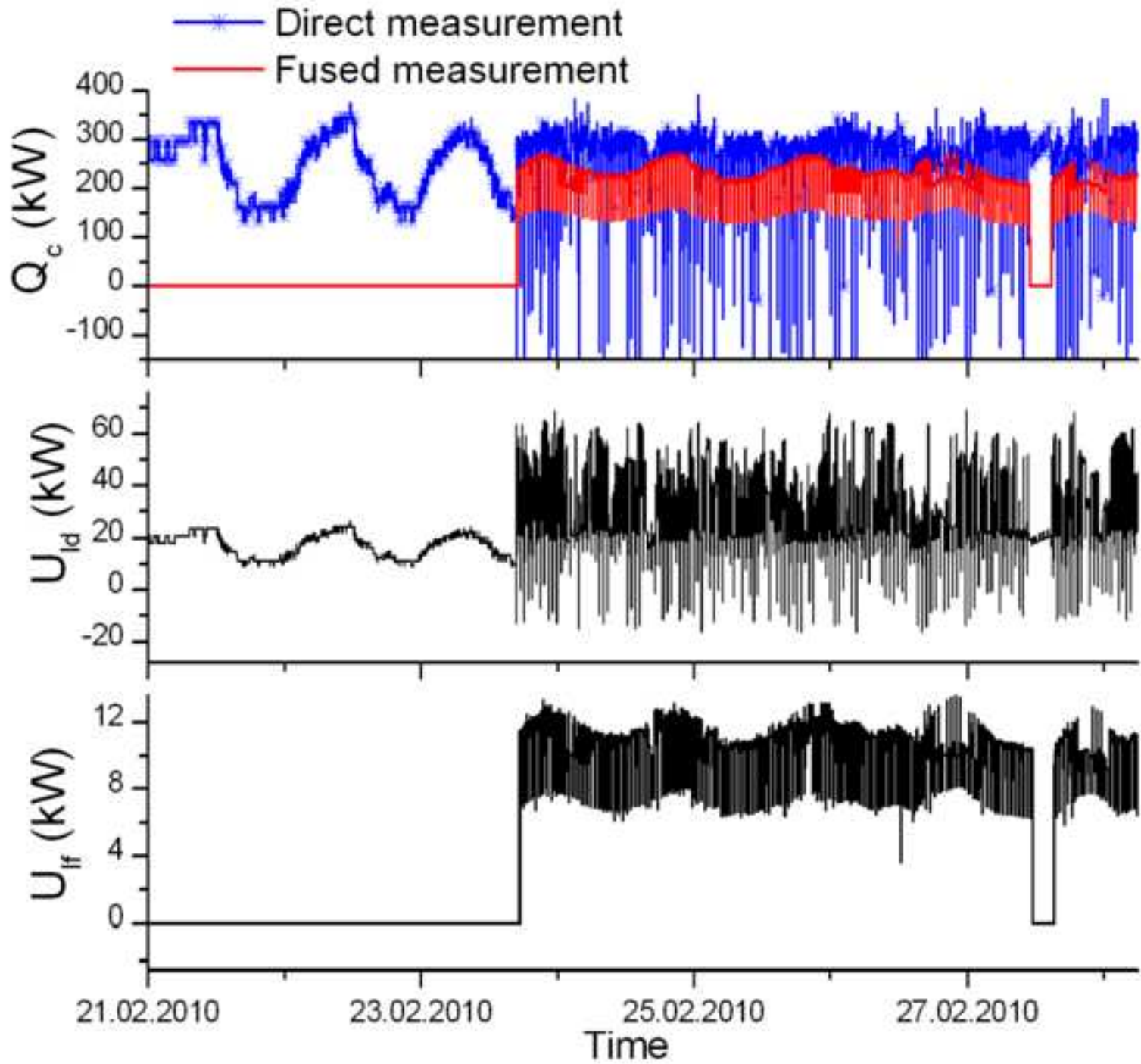


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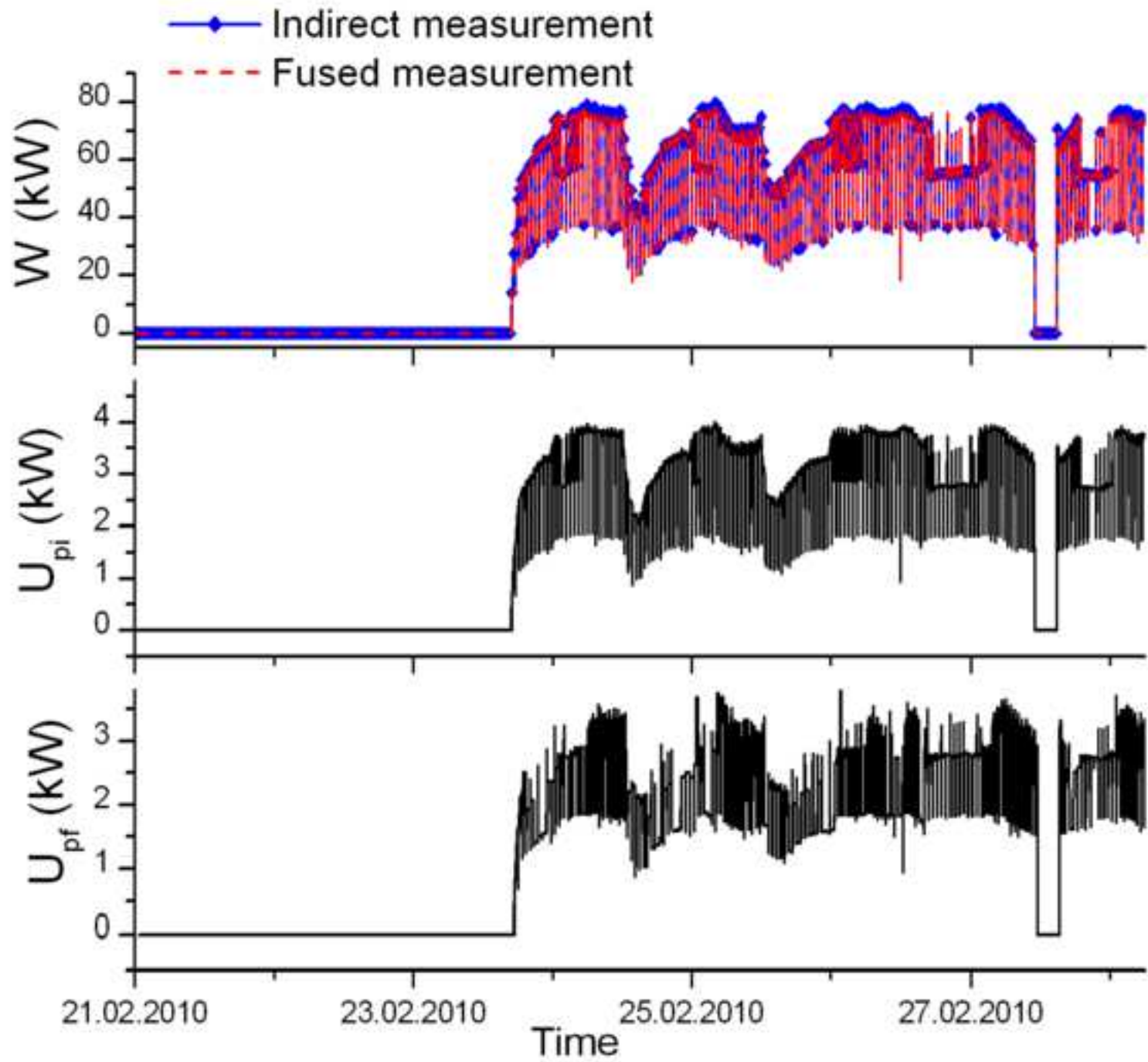


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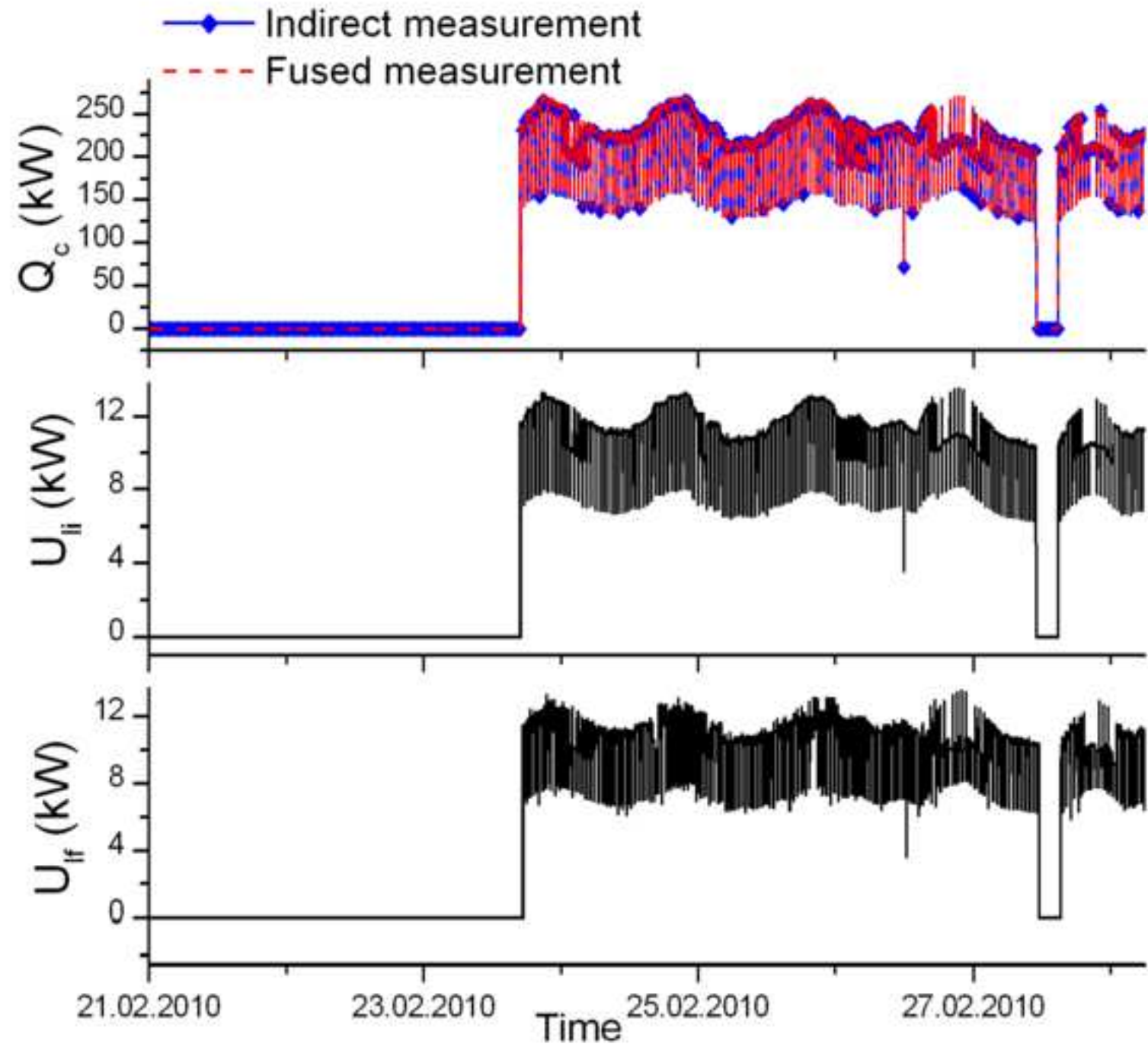


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