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Methods for Measuring Heat Pump Energy Balance

Abstract*. Because applications and operation of heat pump, especially air/water type, are connected with problem based on the principle of these heat sources, we designed methods for measuring complete heat pump energy balance. This will allow us clear up real operation characteristic of this type of heat pump and we gained real data for further analysis.*

Streszczenie. *Opracowano metodę analizy bilansu cieplnego pomp cieplnych. Metoda opiera się na modelowaniu wszystkich źródeł ciepła.* ***Metoda przeprowadzania bilansu energii pomp cieplnych***

Keywords: Heat pump, measurement, energy balance.
Słowa kluczowe: Pompa ciepła, pomiary, bilans energetyczny

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Introduction

This article presents a procedure for designing a measurement methodology to address to a currently very live and frequently discussed topic. That is for sure the utilisation of heat pumps of air/water type and their effective implementation in practical installations. The first chapters contain a description of the object measure and the method for designing the convenient measuring system. The measurement concerns overall energy balance of heat pump incl. heat capacity and secondary parameters associated with operation of this source by directs or indirect means. The second part of this article presents the first partial results based on initial and implemented analysis of the data measured.

Measurement date and location

The energy balance measurement was conducted within an object with intermittent utilisation. The primary heating system in this object comprises air/water heat pump only. The object is situated in the area of Beskydy, Ostravice-Staré Hamry (CZE); and its built-up area amounts to the total of 131 m2. The total heat loss incurred by the object is equal to 4.5 kW in accordance with standard [2]. The measurement period lasts from autumn 2012 to spring 2013.

Measured heat source-heat pump

The primary heating source comprises the air/water heat pump with the nominal output of 8 kW under A2/W35 conditions. The bivalent source is formed by an electric cartridge heater. Appliance connected within the system include a hot water reservoir and heating pipes that form the under floor heating unit.

Table 1. Specifications of measured heat pump

Heat Pump Specification	
Producer/supplier	*HOTJET (CZE)*
Type of heat pump	*air/water (A/W)*
	Compact
Nominal thermal power (A2/W35)	*8 kW*
Bivalent source	*Electric heating element 7,5 kW*
Heating system	*Under floor heating*
Temperature gradient (°C/°C)	*45/35*

Fig.1. Installed heat pump (Šrámek, 2012)

Fig.2. Heated object (Šrámek, 2012)

Measurement engineering design

This part describes the design and schematic representation of the measuring apparatus. The most serious problem was the installation of hydraulic components into the already finished pipeline from heat pump.

Provisions for monitoring of the data necessary were based on the existing measuring equipment and components:

- Heat gauge SIEMENS Megatron 2 (metrologically proven gauge)
- Distribution networks monitor MDS-U
- Measuring bridge SIEMENS ACS tools for heat pumps
- Notebook (XP operation system)
- Data cables and converter

- MDS-U software
- ACS tool software
- MS Excel

The whole measurement system has been designed as automated. In spite of that, we had to spend the first weeks with more frequent monitoring and fine tuning of the system to eradicate some errors, especially in settings of the software equipment. Continuous download of data will enable us conduct checks during measurement and data analysis.

Measurement System Installation

Practical installation of measuring components was performed at the break of September/October 2012. The process dealt mainly with integration of heat gauge into the heat pump return pipe. MDS-u was connected to the distribution board intended solely for supply of power to the heat pump and its components.

Measurement Methodology and Objective

The whole measurement system has been designed to enable retrieval of all heat and electric power data during heat pump operation. The measurement is to retrieve the following data required:

- Heat pump electric input
  - Electric current (A)
  - Electric voltage (V)
  - Power input
    - Active power (W)
    - Reactive power (Var)
    - Apparent power (VA)
- Energy produced by heat pump
  - Total power (kWh)
  - Current power (kW)
- Temperature (°C)
  - Outside temperature
  - Interior temperature
  - Supply and return pipe temperature
  - Heat capacity temperature
- Operation time
  - For compressor
  - For bivalent source

Measurement objective

The measurement focuses on two essential objectives that can be described as monitoring of full heating season and shorter periods. That will enable us retrieve and measure data for assessment of the full heating season as a whole with simultaneous monitoring of rapid changes in the heat pump on/off mode.

First stage

It focuses on the full heating season and determination of the average performance factor and the total consumption of heat pump, which will then enable us convert such data into e.g. actual operating costs for the full heating season.

Second stage

The second stage focuses on monitoring of shorter periods and reaction of the heat pump to rapid changes in heat requirements. These conditions will be also simulated to obtain the data necessary. The measured data helps us observe the behavior of entire system subject to measurement and the data obtained at this level can be used to find mathematical dependencies between the heat source, heat capacity and appliance (heating system).

Relation between

Standards for testing of heat pumps (ČSN EN 14 511 series) have been adopted from the European Commission for Standardization and provide manufacturers with terms and conditions determined for testing of heat pumps. However these terms and conditions are mostly different from the actual operation of a heating system. The matters concerned are especially lower temperature gradients (input and output media temperature) during heat pump testing. [5] A typical example is the air/water heat pump with testing conditions set to 35°C temperature of output fluid. However, the system is designed for operation at higher temperature of 40-45°C. The same case applies to the object measured.

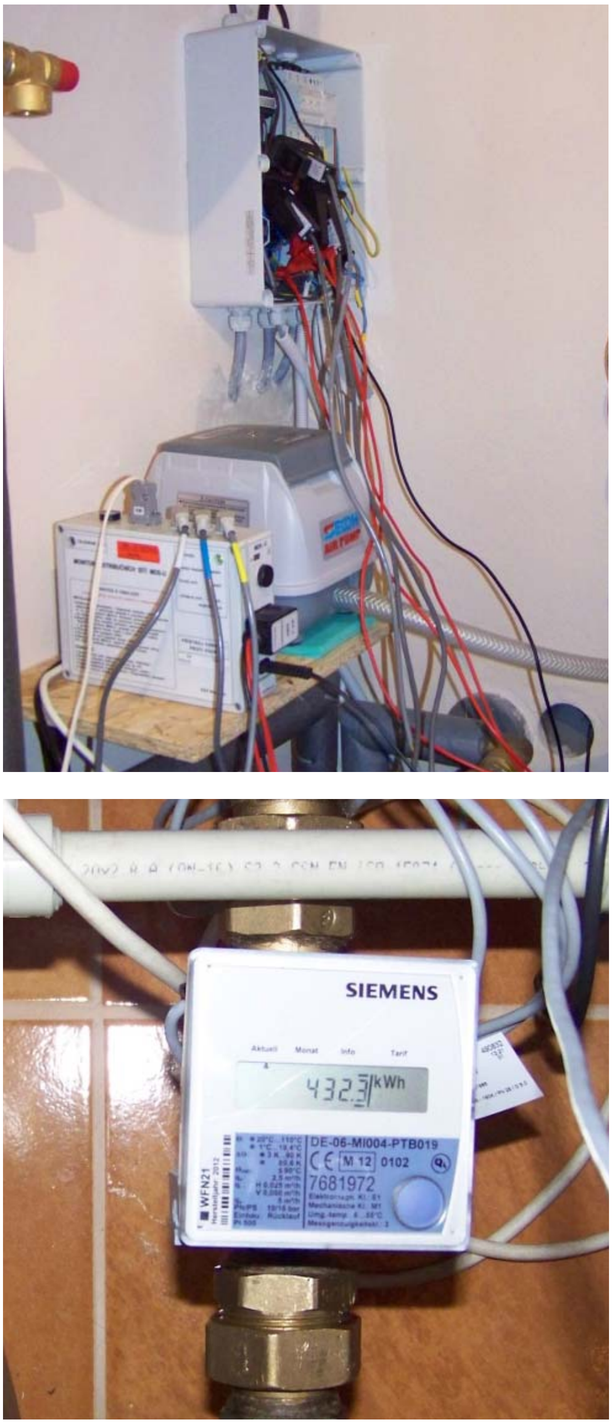

Fig.3. Installed components (Šrámek, 2012)

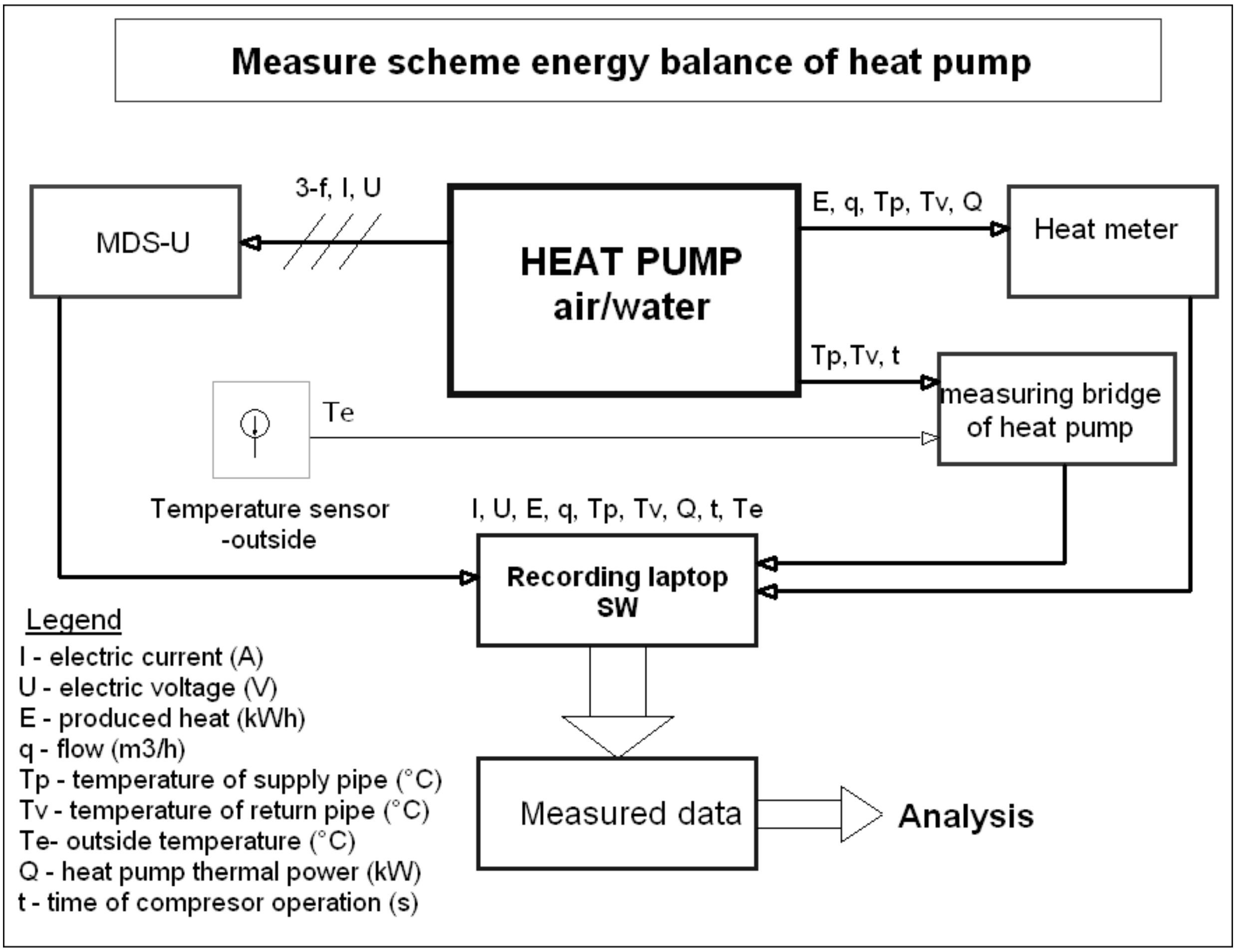

Fig.4. Measuring block diagram

Measured Data Analysis

The data measured is downloaded continuously during the entire process. The data analysis must be preceded by "cleaning" of incomplete data. The initial and subsequent evaluations will be based on the following equations known, there energy equals:

(1) $E = mc\Delta T$ (J)

Heating capacity of heat pump will then be,

(2) $Q = \frac{E}{t}$ (W)

and the performance factor (COP) of heat pump will be

(3) $COP = \frac{Q}{P}$ (-)

where:

E is the energy produced by heat pump (J)
Q is the heating capacity of heat pump (W)
P is the electric power of heat pump (W)
T is the temperature (°C)
t is the time (s)
COP is the coefficient of performance (-)

Determination of Value Position and Variability Extent Depending on Temperature

Our aim is to clear given values depending on outside temperature, to eliminate the so called outliers. Those are transient conditions established during operation of heat pump due to thermal inertia. For example, the data within measured interval show the heating capacity corresponding with the operation value, yet the electric input value is produced with the compressor disconnected and the component running is the circular pump only. That is a common transient effect but the calculation of performance factor using the equation 3 produces a "nonsense" result. This is the case, when such operation conditions with no significant effect from the overall data file point of view need to be filtered out. In spite of the above, those will be addressed in the next analysis to determine the frequency of such outliers in order to minimize the consequence of removal of these transient effects.

Shorth a Modus

There are two options to avoid the effect of outliers, i.e. such values outside the real option to operate the air/water heat pump.

The first one deals with utilisation of determination of the so called Shorth and Modus. Determination of Shorth will indicate 50 % of values from the said file that lie within the shortest interval possible. Our case will deal with the COP value, for example; that contains 50 % value of COP lying within the shortest interval. The procedure will help us obtain the interval length, top and bottom COP values, which oscillate depending on the outside temperature measured. However, if there is a large amount of outliers, i.e. values too different from the mass data file, it will have a strong impact on situation of the top and bottom thresholds of the specific interval. This case implies need for determination of frequency of outliers.

Outliers

Elimination of outliers will be based on technical abilities of heat pump, which can generally operate within COP values range of 1-6. However, that is very subjective insight on the data file. Elimination of this subjective marginal condition will be done using identification of outliers. The identification will enable us consider, which interval measured still characterizes the actually possible operation of heat pump and its already transient nature due to thermal inertia, as mentioned in chapter above. For the purpose of outliers' identification, the data file must be split into the so called partial data files to define quartiles of particular COP data measured or calculated with respect to the outside temperature. Further step includes determination of bottom and top quantiles for the specific value. An outlier is then defined as such value, which is further than 1.5 IQR from the bottom or top quantile; that is the interval extent in accordance with:

(4) $$IQR = x_{0,75} - x_{0,25}$$

An outlier (further referred to as "OP" only) is then identified within the data file as follows:

(5) $$(x_i \leq x_{0,25} - 1{,}5IQR) \vee (x_i \leq x_{0,75} + 1{,}5IQR) \Rightarrow x_i\ OP$$ (J)

Data File - December 2012

Whenever possible the data measured of interest for us should define full range of temperatures for heat pump operation (-18°C to +20°C). The temperature range in December was limited from -11 up to +9.55°C, which is interesting with reference to functioning principle of the air/water pump. The data obtained in December was used to perform partial calculations. These produced the average performance factor, the total energy produced and the total energy consumed. As far as the performance factor is concerned, the data file was processed using the coefficient values of 1-4. That helped us filter out the performance factor beyond these threshold conditions.

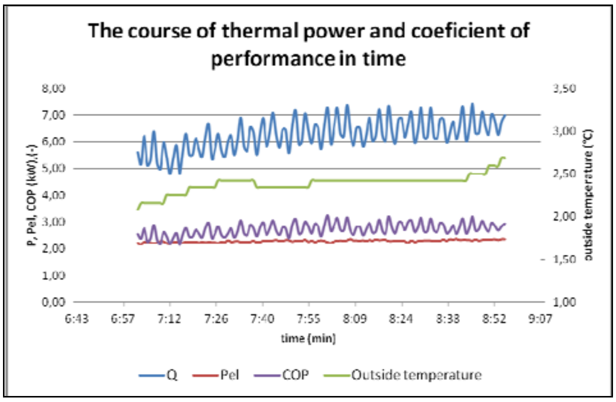

Fig.5 Diagram with thermal power and COP dependence in time

Data File Correction

The initial data file comprises 37,814 values/lines. The data was measured within 1-minute intervals. The data file is not perfectly complete but it includes a continuous section from 1.12.2012 till 29.12.2012. The interval measured (1 minute) seems sufficient for description of heat pump operations dynamics and we have taken on adjustments to eliminate incorrect and incomplete data only. Apart from filtering the incomplete data out, the data file has been further split to heat pump operation and downtime conditions. The data file showing mere operation of heat pump then includes 10,796 lines only.

Table 2. Measured data

Data File for December 2012		
Number of rows/lines	37,814	-
Heat pump operation	10,796	-
Off heat pump operation time	26,169	-
Removed data	849	-
Outside temperature (min.)	-11	°C
Outside temperature (max.)	9.55	°C
Average temperature	1.17	°C
COP (average)	2.53	-
Produced power	1461.75	kWh
Electric power	665.78	kWh

Data Presented

The data obtained by measurement has been processed into a simple table (Tab. 2) and graphic illustration. Table 2 shows the data obtained, where the most vital aspects are electric power produced and supplied respectively. These power values are considered as total and determination prior to clearing of the data file. Using the equation 3 will generate the average COP value of 2.19, which is a fairly significant difference compared to 2.35 stated in Table 2. The value of 2.53 has been calculated from the data file, which has been cleared of incomplete data; further specification of adjustments to the data file requires limitation of removal of vital data within. The aim is to achieve mutual approximation of these COP values to reduce the uncertainty during data file analysis.

The first demonstration of result is shown in Fig. 5, which illustrates the dependency of heat output, power input and performance factor within a continuous time interval. Fig 5 shows gradual change of output depending on the outside temperature over time.

Following the filtration of data from the whole data file allowed us to work with a sample of sufficiently representative extent. Illustration of output and performance factor after change of outside temperature has been done within the range between -11 and 10 °C. The data has been illustrated in Fig.6 and provided with trend flow line for better transparency. That also helped us determine the functional dependency of variables under examination. However, these dependencies have been illustrated with certain unreliability, which we will try to eliminate during next analysis to achieve a more acceptable data. The unreliability is evident mainly in the illustration of heat output (Q) as well as the performance factor (COP). That is caused mainly by inertia of thermal effects occurring between the heat pump and heating circuit (accumulation).

Conclusion

The methodology of measurement presented in this article and the data analysis outlined here represent actual presentable opportunity to obtain data about operation of air/water heat pumps to be further developed to establish the heat asynchrony in heating of the object concerned. The objective is to obtain the data for full heating season to establish the functional dependency of heat pump output within basically the whole temperature range as required. The functional dependency, together with mode/s of heating in the object concerned will enable us innovate sizing of heat pumps to ensure more effective utilization of their options. This is also associated with monitoring of parameters of charging and discharging of the heat capacity

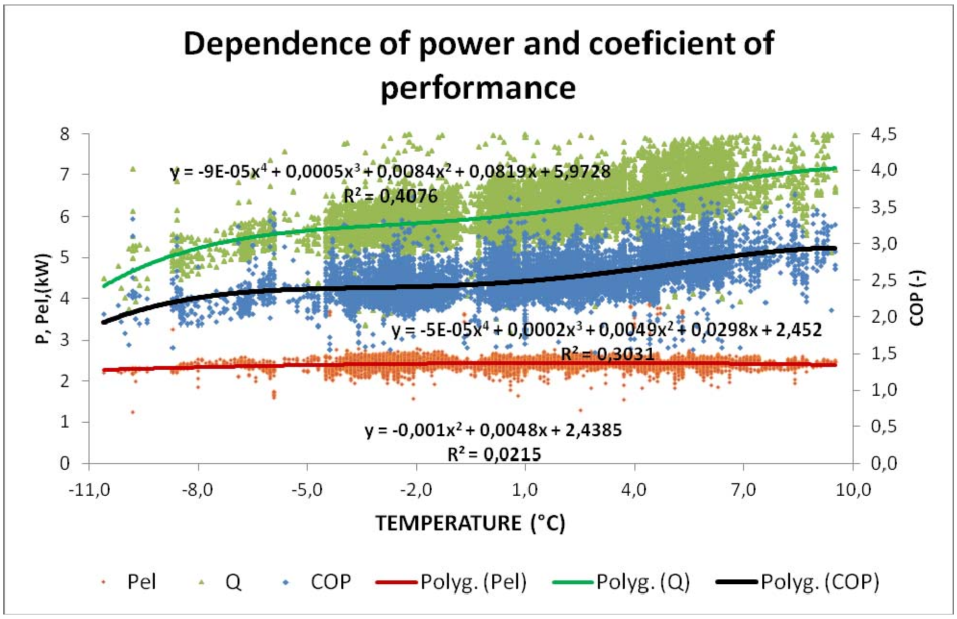

Fig.6. The dependence coefficient of performance (COP) and power according to outside temperature

integrated within the system. We can further work on improved effectiveness of design with respect to tank size.

The extensive data file enables derivation of various dependencies and variables in the heat pump operation, yet the process requires appropriate alteration of data file, as indicated in this articles. The output data observed in December, as shown in Fig.6, provide a truly detailed description of operation of the air/water heat pump. Subsequent derivation of functional dependency of the heat pump output will help us assess the correct selection of heat pumps with different output characteristics (stronger or weaker) with regard to the defined entry terms and conditions defined. The outlined analysis will be further finalized pursuant to complete data from full heating season. The next step will mainly concern a more detailed clearing and analysis of the data file and reduction of unreliability of dependencies illustrated here.

The outcome from this analysis will comprise especially optimization of heat pump behaviour with respect to operation and reliability aspects, reduction of investments as well as direct operating costs of heating. The proposed methodology of measurement is then aimed towards obtaining relevant data that is even measured in duplicate under some circumstances. That will provide us with the necessary data wrap.

This method has enabled us clear the data file of error and incomplete data values. Further reduction of the data file must be conducted very carefully to avoid removal of vital yet seldom operating conditions. These conditions will be also identified below. [6]

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