Evaluation and Monitoring of Effectiveness of Heat Pumps via COP Parameter

Petr Vojcinak, Mojmir Vrtek, Radovan Hajovsky, Jiri Koziorek

Abstract**—**This paper deals with some evaluation and monitoring of effectiveness of heat pumps located at the Small Research Polygon (SRP) district, whereas very important parameter of these HPs is so-called coefficient of performance (COP), which is solved from various viewpoints here. The first part is focused on the COP parameter solved from the direct energy input, which is resolved to so-called exergy in the second part. Some recalculation mechanism is also done. All these methods are helpful for evaluation, but each of them has its specific application. The third part of this paper is centered on some description of a SRP technology and monitoring of the parameters needed to calculate a COP parameter value of the SRP heat pumps.

Keywords**—**Coefficient of performance (COP), DCOP parameter, ECOP parameter, effectiveness, exergy, ExCOP parameter, heat pumps, ICOP parameter, primary energy, the Big Research Polygon (BRP), the Small Research Polygon (SRP).

I. Introduction

First installations of heat pumps have practically expanded since 1970s in the USA in connection with the 1973 oil crisis. In the Czech Republic this phenomenon has started since 1990, when the first high-quality heat pumps were especially imported from Germany, Austria, and Sweden. Although a gradual progress of their installations took place during the whole time of 1990s, but a massive expansion has just started since 2000 due to advantageous governmental support programmes. [4]

Hence in 2006, a multifunctional building of Nova aula VSB – TUO became one of the most extensive sui generis projects realized in the Czech Republic, where heat pumps have already been installed. This building is used not only for tutorial and trainee, but also for ceremonies (e. g. graduation ceremonies, the Academic Senate councils etc.), congresses, international conferences, and cultural activities (e. g. concerts, exhibitions etc.). [5]

At the present time some total number of heat pump installations in the Czech Republic is not known, nevertheless it can be guesstimate on account of a number of ultimate consumers, who are registered by Czech distribution companies – e. g. in 2008 they registered about 15000 delivery points. For heat pump delivery's part, in 2007 it was supplied about 3600 heat pumps (49 MW total power), in 2008 that was about 4000 heat pumps (55 MW total power) [1], whereas it assumes that a kind of all the heat pumps is compressor-based. Nowadays absorption heat pumps also expand.

There are more technical factors about heat pump itself, including the efficiency of heat pump increasing though heat pump cycling, using material technology to simplify the structure of heat, reducing heat pump costs, using monitoring technology to improve the reliability of heat pump. [10]

II. Coefficient of Performance (COP)

A. General definition

Principle of heat pump activity consists in an accumulation of low temperature heat (Q_{LT}; usually heat from natural resources or secondary energy sources) and its evaluation via power energy (A) to reach higher temperature heat (Q_{HT}) for thermal heating. Fig. 1 shows some comparison between direct heating (e. g. resistance heating, combustion products etc.) and heating via heat pump – in the case of an ideal lossless energy balance. [2]

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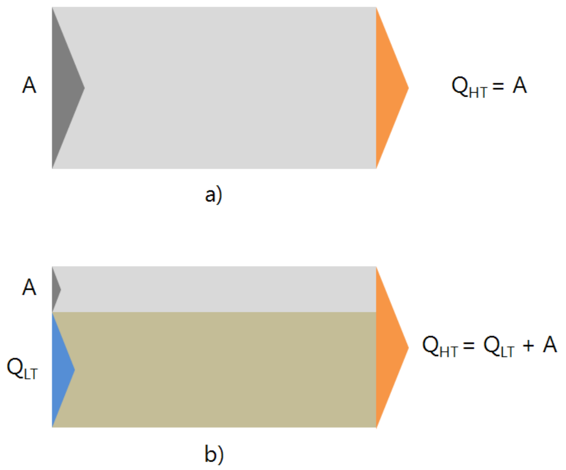

Fig. 1 comparison between direct heating (a) and heating via heat pump (b) – the case of ideal lossless energy balance

Parameter of COP (ε_T) is a basic effectiveness ratio of heat pump activity. This parameter could describe the quality of heat/cold conversion [9]. In this case, it is Q_{HT}-to-A ratio mathematically represented by (1) in an energy form.

$$\varepsilon_T = \frac{Q_{HT}}{A} \Rightarrow \frac{Q_{HT\,[J]}}{A_{[J]}}. \tag{1}$$

If we augment a right-hand side of (1) by time (typically in seconds), it is able to represent (1) in a power form.

$$\varepsilon_T = \frac{Q_{HT}}{A} \Rightarrow \frac{Q_{HT\,[J]}/t}{A_{[J]}/t} = \frac{Q_{HT\,[W]}}{A_{[W]}}. \tag{2}$$

The energy form (second members typically are in joules) of COP parameter mentioned in (1) is usually used for average COP parameter formulation namely for a longer time period (i. e. month, year).

The power form (second members typically are in watts) of COP parameter mentioned in (2) could be used for momentary COP parameter formulation namely for a limit time interval, when $t = (t_2 - t_1)$.

Next equations are based on the energy form only, but it is able to understand these balance equations in the power form.

COP parameter, generally defined in this way, does not define borders of evaluated energy system, so it is required to concretize them.

B. Internal COP (ICOP)

If we have just concreted a system border inside thermodynamic circulation and if system quantities – used for a COP parameter calculation – are defined from some thermodynamic changes of operational substance (usually coolant enthalpy changes), then we talk about so-called internal COP.

C. External COP (ECOP)

Real processes, which are in progress during crossing of mentioned system border (i. e. heat transfer, supply of power energy), breed some transformation and transfer energy dispersions defined with:

- effectiveness of heat exchangers,
- degradation of heat transfers,
- heat losses,
- parasitic heat gains,
- actuation effectiveness of heat pump.

If we shift the system border to get external I/O of heat pump, we can accept it as a black-box system, when:

- inputs are represented by low-energy heat and heat pump actuation energy (i. e. electrical energy for compressor-based heat pumps, heat for absorption heat pumps),
- outputs are represented by thermal heat.

If a value of COP parameter based on these I/O quantities, then we talk about so-called external COP parameter.

D. Total COP (TCOP)

Evaluation of the ICOP and ECOP parameters is very helpful for producers of heat pumps, when it is able to optimize a design of cooling circuit, choice of coolant and other components etc.

Parameter of TCOP is not only predicative for heat pump users, but also this is declared in technical documentation and based on the results of standardized tests e. g. for compressor-based heat pumps. [2]

Equation (3) is a mathematical description for the ideal lossless energy balance of heating via heat pump (see Fig. 1).

$$Q_{HT} = Q_{LT} + A. \tag{3}$$

Equation (3) also denotes, that a value of COP parameter always is greater than 1, because

$$\varepsilon_T = \frac{Q_{HT}}{A} = \frac{Q_{LT} + A}{A} = 1 + \frac{Q_{LT}}{A}. \tag{4}$$

This theoretical reason denoted in (4) is relevant for internal coefficient of performance (ICOP) only, because if it were not, any thermodynamic circulation would not be realized. On the other hand, mentioned condition need not be relevant for external coefficient of performance (ECOP), because a value of ECOP parameter could be smaller than 1, when power energy utilization is extremely ineffective. The similar reason can be applied to total coefficient of performance (TCOP), too.

Following example illustrates practical effectiveness of badly structurally designed heat pump, whereas some graphic charts – i. e. graphs of heating power ($Q_{HT[W]}$), electric input ($A_{[W]}$), and ambient air temperature ($t_{A[°C]}$) of heat pump (air/water type) – are shown in Fig. 2.

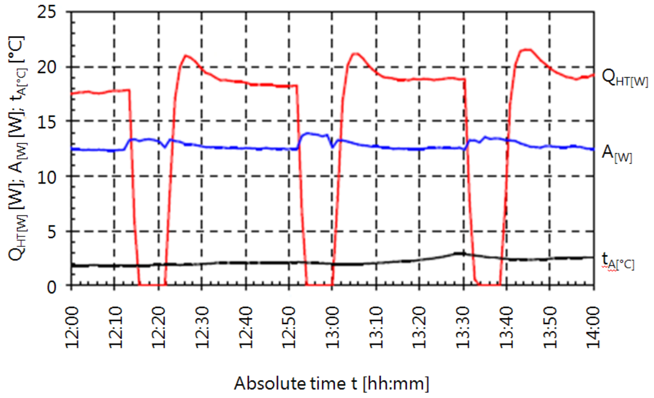

Fig. 2 graphic illustration of practical effectiveness of badly structurally designed heat pump – an activity time period of this heat pump is two hours

As evidenced by Fig. 2, values of electric input are very high in comparison with values of heating power during the heat supply period, whereas value of TCOP parameter equalled to 1.48 for whole measurement time. We chosen very incorrect method for evaporator defrosting via a hot-air fan, which has electric input comparable with heat pump one; its red graphic chart (see Fig. 2) is distinguished by six-minute failures of heat supply. If we include some consumption of defrosting cycle, which need not be so long in dependence on current temperature and ambient air humidity, then value of TCOP parameter equals to 1.17, whereas output temperature of heating water equals to 37.0 °C or 310.15 K.

If we recognize, that mentioned heat pump really was more efficient than direct heating, then we expect from it better usable properties.

E. Direct COP (DCOP)

If the parameters of ICOP, ECOP, and TCOP are referred to power energy, specified by concrete kind and its quantity (i. e. direct energy inputs crossing the energy system border near the physical border of heat pump product), then we talk about so-called direct COPs.

III. Comparison of DCOPs for Various Kinds of Heat Pumps

A physical principle of heat re-pump is based on reversed thermodynamic cycles. For easier understanding of evaluation philosophy, there are some ICOP analyses in this chapter, but the same philosophy can be used for other kinds of DCOPs.

A. Block diagrams of evaluated heat pumps

1) Compressor-based heat pumps

This kind of heat pump makes use of thermodynamic heating principle, when temperature increase is realized by thermodynamic condition change of gas or steam (i. e. adiabatic compression). During this process it is required to provide for compressor actuation (A). Block diagram of compressor-based heat pump is shown in Fig. 3.

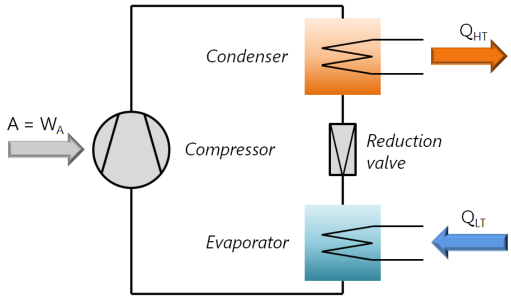

Fig. 3 block diagram of compressor-based heat pump with its important parts (compressor, condenser, reduction valve, and evaporator), and labels of quantities

A value of DCOP parameter of this heat pump kind is calculated in compliance with (1), i. e. $A = W_A$, see (5).

$$\varepsilon_T = \frac{Q_{HT}}{A} \Rightarrow \frac{Q_{HT}}{W_A}. \quad (5)$$

Due to rise in heat rejected from condenser, a value of COP parameter increases with evaporator temperature. [11]

2) Absorption heat pumps

This kind of heat pump makes use of absorbing properties of medium pair – pairs of NH_3/H_2O (ammoniac/water) or $H_2O/LiBr$ (water/lithium bromide). Block diagram of absorption heat pump (NH_3/H_2O type) is shown in Fig. 4.

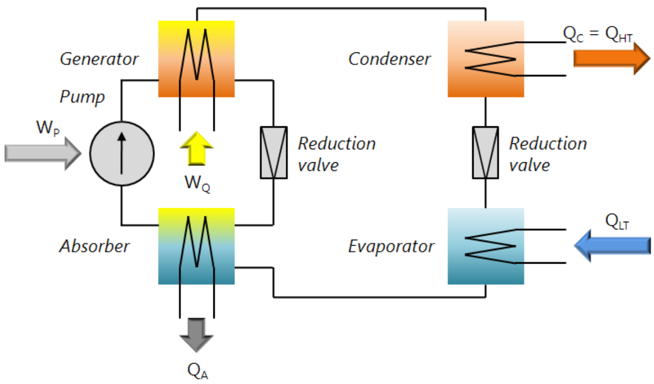

Fig. 4 block diagram of absorption heat pump with its important parts inside the first circuit (pump, generator, reduction valve, and absorber), inside the second circuit (condenser, reduction valve, and evaporator), and labels of quantities

In contrast to compressor cycles there is some fundamental supply energy (W_Q) in the form of medium-potential heat or high-potential one. For heating it is able to use not only heat of condensation ($Q_C = Q_{HT}$), but also heat of absorption (Q_A). Although, a pump is also required for operating of absorption cycles, its consumption is imponderable in comparison with supply energy, i. e. $W_Q >> W_P$.

A value of DCOP parameter of this heat pump kind is calculated like this, see (6).

$$\varepsilon_T = \frac{Q_{HT}}{A} \Rightarrow \frac{Q_C + Q_A}{W_Q + W_P} \cong \frac{Q_{HT}}{W_Q} . \quad (6)$$

B. Comparison of DCOPs

Values of DCOP parameter for compressor-based heat pumps (DCOP parameter value typically equals to 2.5 till 5.0) are greater than values of DCOP parameter for absorption heat pumps (DCOP parameter value typically equals to 1.2 till 1.6), so absorption heat pumps have been underestimated for a long time. Dissonance consists in evaluation philosophy of supply energy, whereas it is required to differentiate the form of this energy (i. e. heat form or work form).

Our approach to evaluation is based on the reversible Carnot cycle between temperatures of T_{HT} and T_{LT}, and applied for some models of heat pumps. A temperature/entropy diagram of the reversible Carnot cycle is shown in Fig. 5 and corresponding mathematical equation for DCOP parameter calculation is in (7).

$$\varepsilon_T = \frac{Q_{HT}}{A} = \frac{Q_{HT}}{W_A} = \varepsilon_{T(Carnot,A)} = \frac{T_{HT}}{T_{HT} - T_{LT}} . \quad (7)$$

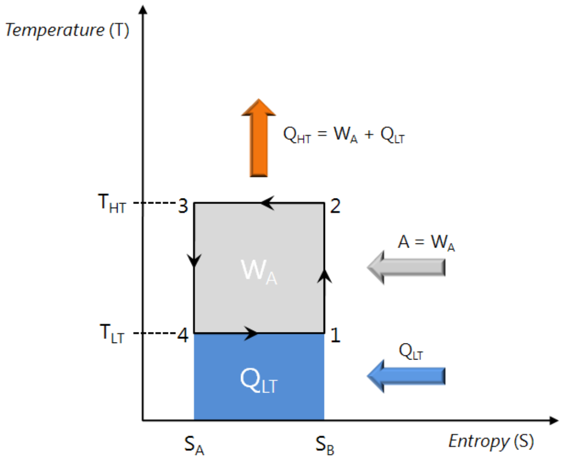

Fig. 5 temperature/entropy diagram of the reversible Carnot cycle for heat pumps powered by mechanical work – compressor-based heat pumps

If supply energy of absorption heat pump (W_Q) is represented in the form of heat, then it is required to use some modification of the Carnot cycle (see in Fig. 6), when a temperature/entropy diagram includes not only the reversible Carnot cycle, but also the clockwise Carnot cycle, because only part of power energy ($A = W_A$) of totally supplied energy (W_Q) – the right part of the diagram in Fig. 6 – could join the re-pump process – the left part of the diagram in Fig. 6.

This reason can be achieve via exergy analysis of absorption cycle. The DCOP parameter value calculation, based on the diagram in Fig. 6, could be mathematically defined like this, see (8).

$$\varepsilon_T = \frac{Q_{HT}}{A} \Rightarrow \frac{Q_{HT}}{W_Q} = \eta_{T(Carnot)} \cdot \frac{Q_{HT}}{W_A} = \varepsilon_{T(Carnot,Q)} . \quad (8)$$

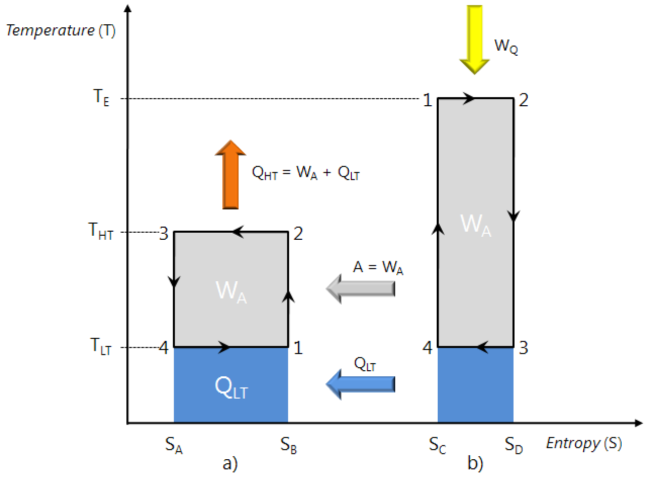

Fig. 6 temperature/entropy diagram includes the reversible Carnot cycle (a) and the clockwise Carnot cycle (b) – absorption heat pumps

Parameter of $\eta_{T(Carnot)}$ denotes so-called thermal efficiency of the clockwise Carnot cycle. Equations (7) and (8) also denote, that parameter of $\varepsilon_{T(Carnot,\ A)}$ is always greater than parameter of $\varepsilon_{T(Carnot,\ Q)}$, because

$$\varepsilon_{T(Carnot,A)} > \varepsilon_{T(Carnot,Q)} \Rightarrow \eta_{T(Carnot)} = 1 - \frac{T_{LT}}{T_{HT}} < 1 . \quad (9)$$

Effectiveness comparison of various kinds of heat pumps via DCOP parameter values does not respect a kind of input supply energy and its quality. Physical quantities of mechanic work and heat are carriers of various energy kind and quality; therefore, it is not possible to compare 1 kWh of heat (with temperature equals to 100 °C) and 1 kWh of mechanical work. That is a reason, why it is not possible to compare the DCOP parameters of various kinds of heat pumps – in this case we talk about compressor-based ones, and absorption ones only.

C. Exergy COP (ExCOP)

As noted previously, some dissonance consists in quality of supply energy, whereas it is required to differentiate the form of this energy. Well, exergy analysis of input energy enables to compare various kinds of heat pumps and COP parameter is calculated via (1), but a denominator of (1) includes a member of input exergy (E_A), which is fed into cycle by power energy, in the place of a member of power energy (A).

It can be accepted exergy as a part of power energy, which could be transformed into other kind of energy. While quantities of mechanical work and electric work are fully transformed (i. e. condition of 100 % exergy, which is dependent on its temperature level and ambient temperature), heat is not fully transformed. [3] Exergy is defined as the maximum work, which can be produced by some system or steam of matter or energy as it comes to equilibrium with a reference environment. Exergy analysis is a method for assessing systems and processes. It differs from energy analysis and is more practical. Energy analysis is based on the first law of thermodynamics, while exergy is based on the first and second laws. The second law addresses energy quality and asserts, that exergy is destroyed during irreversible process. Other second-law-based methods exist, but exergy is one of the most common. Unlike energy, exergy is not conserved and the initial exergy is destroyed at least in a part by process irreversibilities. [8]

In the case of compressor-based heat pumps (see Fig. 5), input energy in the form of mechanical work equals to input exergy, so a mathematical equation of ExCOP parameter calculation (for compressor-based heat pumps) is identical with (1).

In the case of absorption heat pumps (see Fig. 6), it is required to define E_Q parameter value (exergy) of W_Q parameter value (totally supplied energy) at T_E temperature (exergy temperature). If T_{LT} temperature equals to ambient temperature, then mentioned exergy is just equalled to the part of W_A (power energy), which partakes of heat re-pumping. Equation (10) is a mathematical equation of ExCOP parameter calculation (for absorption heat pumps).

$$\varepsilon_T = \frac{Q_{HT}}{E_Q} = \frac{Q_{HT}}{W_Q \cdot \eta_{T(Carnot)}} = \frac{Q_{HT}}{W_A} = \varepsilon_{T(exergy,A)} \,. \qquad (10)$$

Equation (10) also denotes, that we can reciprocally compare the ExCOP parameters of various kinds of heat pumps or heat pumps making use of some combinations of input energies.

For example, in the cases of absorption heat pumps and definition of a value of so-called total exergy coefficient of performance (TExCOP), we reason about these exergies:

- evaluation of heat exergy is primary supply energy,
- exergy supplied via actuation of cooling circuit pump,
- exergy fed to additional elements – circulation pump actuations for heat-transfer fluid of evaporator and heater power circuit of absorber/condenser.

This described evaluation philosophy could be applied for a comparison of COP parameter for other types of heat pumps, e. g. thermo-electric ones.

IV. Effectiveness of Heat Pumps from Macroeconomic Viewpoint

Mentioned evaluation approaches enable some effectiveness comparison, when:

- DCOPs are for the same kinds of HPs,
- ExCOPs are for various kinds of HPs.

On the other hand, these approaches disable to achieve some evaluation from macroeconomic viewpoint, i. e. what benefit of HP appointments (with the view of energy savings) is for consumption minimization of primary energy sources in the Czech Republic.

In this case we reason about lossless transformation and energy transfers to elucidate this evaluation philosophy.

A. *Compressor-based HPs powered by electric motor*

In the case of this heat pump kind, mechanical work, supplied by electric motor, is transformed from high-efficiency electric energy.

For this HP kind there is some limit for minimal value of average annual DCOP parameter equals to 3 (sometimes 4) in the Czech Republic. Consequently, macroeconomic consideration supposes, that electric energy is mainly produced via thermal-power plants (condenser type, 33 % efficiency), so heat pump has to “re-pump” no fewer than 67 % of low-potential heat to reach for the state, when a value of finite heat (Q_{HT}) should be sufficient to a value of primary (supply) energy (W_{PR}), joined the technological process.

Balance diagram (for macroeconomic analysis) of compressor-based heat pump is shown in Fig. 7, where Q_Z parameter denotes a heat removal via cooling towers.

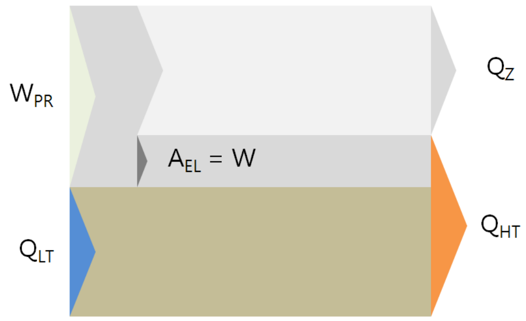

Fig. 7 balance diagram of compressor-based heat pump powered by electric energy, produced via thermal power-plant (condenser type)

If some country produces the most of electric energy in water-power plants, wind-power plants, and photovoltaic-power plants, then a value of DCOP parameter should be greater than 1 to reach heating via this electric energy, see Fig. 8.

Fig. 8 balance diagram of compressor-based heat pump powered by electric energy, produced via non-thermal power-plants (i. e. water-power, wind-power, and photovoltaic-power ones)

B. *Compressor-based HPs powered by explosion engine*

In the case of this heat pump kind, quantities of Q_{EC} (heat obtained by engine cooling) and Q_{BG} (heat of burnt gas) are the parts of finite heat (Q_{HT}), see Fig. 9.

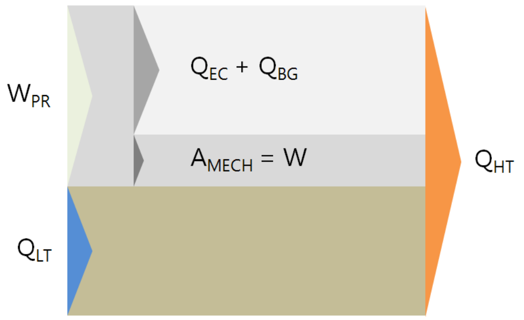

Fig. 9 balance diagram of compressor-based heat pump powered by explosion engine

C. Absorption HPs

As noted previously, in the case of this heat pump kind, heat is the fundamental direct "actuation".

Fig. 10 balance diagram of absorption heat pump

Absorption heat pump becomes an interesting HP kind, if that is powered by waste heat.

D. Primary COP (PCOP)

From above-mentioned balance diagrams, it results, that effectiveness of heat pumps (evaluated from macroeconomic viewpoint) refers to input energy (i. e. power energy), whereas if this is a secondary kind energy, then it is required to evaluate with respect to primary energies, too.

Analogously to (1), we can define so-called primary COP, (which considers quantity of primary energy, joining technological processes) like this, see (11):

$$\varepsilon_T = \frac{Q_{HT}}{W_{PR}} = \varepsilon_{T(primary)} \,. \qquad (11)$$

In the case of absorption heat pumps and heat pumps powered by electricity from RS electric power plant, PCOP parameter is ideally equalled to DCOP parameter; in the case of other types of HPs, it is different.

Some comparison of PCOP and DCOP parameters is shown in Fig. 11, where graph legend denotes some characteristics for these kinds of heat pumps:

- EM-STP – compressor-based HPs, powered by electricity from steam turbine power plant (thermal kind of power plant),
- EM-EE – compressor-based HPs, powered by explosion engine,
- EM-RS – compressor-based HPs, powered by electricity from RS electric power plant (non-thermal kind of power plant),
- ABS – absorption HPs.

Fig. 11 shows philosophy for evaluation of heat pumps from macroeconomic viewpoint.

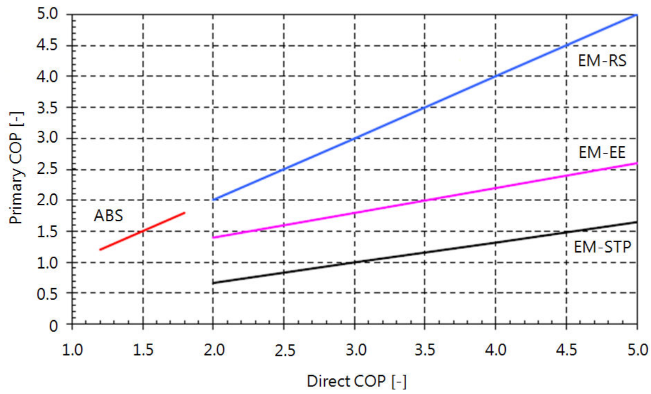

Fig. 11 primary COP graphical dependence on direct COP for various kinds of heat pumps (ABS, EM-RS, EM-EE, and EM-STP)

Real values of COP parameter for absorption HPs usually equal to interval (1.2, 1.8). If we consider some absorption HP (with COP parameter equalled to 1.5), then COP parameter value of the equivalent compressor-based HP (powered by electricity from steam turbine power plant) must be equalled to 4.5 from viewpoint of primary energy utilization.

If we compare absorption HPs with compressor-based ones, then COP parameter value (DCOP parameter relative to mechanic work) of the equivalent heat pump powered by explosive engine must be equalled to 2.2 to reach the state, when PCOP parameter of absorption HP equals to 1.5.

Heat pump powered by explosive engine could be simply (at 100 % effectiveness of electricity transmission and transformation) considered as a heat pump powered by electricity produced during the combined heat and power technology, e. g. in some thermal power station, where heat (analogous to mentioned quantities of Q_{BG} and Q_{EC}; see Fig. 9) is efficiently used. From macroenergetic viewpoint, it is required to include these quantities in a quantity of total thermal heat (Q_{HT}).

For detailed analysis, it is required to reason about so-called modulus of state total energy production of electricity, whereas these resources would be limited by the region, located between the characteristics of EM-STP and EM-EE.

V. Monitoring of COP Parameter

At the district of VSB – Technical University of Ostrava there are two experimental polygons used for applied research of any changes of rock massif:

- the Big Research Polygon (BRP),
- the Small Research Polygon (SRP).

Installation of measurement systems for these research polygons was realized to acquire some relevant data about heterogeneous system behaviour of a ground exchanger for heat pumps, installed at the district of the Aula VSB – TUO building (for the BRP) and the building of the Energy Research Centre (for the SRP, see Fig. 12). Ground exchanger temperature measurement during operation of heat pumps is mainly used for mathematical modelling and simulation of space thermal exchange, and system behaviour prediction in future. [4]

Fig. 12 the Energy Research Centre building located at the district of VSB – Technical University of Ostrava

A. The Big Research Polygon (BRP)

The BRP is mainly determined for rock heat take-off influence monitoring. There are 10 Swedish heat pumps (type of IVT Greenline D70; ground/water type; R407C coolant) with total power of 700 kW at the Aula VSB – TUO building (also the Nova aula building). This polygon has 110 operating boreholes with 140 m depth in the form of low-energy heat source. These boreholes are also sorted with the distance of 10 m between lines, equipped with some double U-tube polyethylene (PE) collectors, and fixed by concrete-bentonit compaction grouting compound.

The BRP configuration is as follows:

- 10 energy-exploited boreholes – they are connected to heat pumps, whereas input line includes 2 temperature sensors in depths of 20 m and 100 m; output line includes 4 temperature sensors in depths of 20 m, 50 m, 100 m, and 140 m,
- 5 measurement boreholes – they are not connected to heat pumps, whereas 4 temperature sensors are situated in depths of 20 m, 50 m, 100 m, and 140 m,
- 1 groundwater borehole.

Primary circuit of BRP heat pumps is infused with 18000 dm^3 of heat-carrier antifreeze fluid. There are 5 junction wells for these 110 boreholes (i. e. 22 boreholes for 1 junction well, see Fig. 13a), whereas each junction well has its own circulation pump (see Fig. 13b). Heating systems consist of heated floor, some heating bodies, and air-conditioning, and they are designed for low-temperature gradient. [7]

TABLE I

VALUES OF HEAT POWER, ELECTRIC SUPPLY, AND COP PARAMETER FOR SOME BRP HEAT PUMP IN COMPLIANCE WITH THE EN 255 STANDARD [6] [7]

Configuration [°C]	P_{HT} [kW]/P_{EL} [kW]	ε_T [-]
0/35	67.8/16.7	4.06
0/50	69.8/22.3	3.13

Meaning of used SI units; °C = Celsius degree, W = watt.

Fig. 13a BRP heat pumps located at junction wells of the Nova aula building [7]

Table I includes some values of power parameters (i. e. values of heat power $Q_{HT[W]}$, electric supply of heat pump P_{EL}, and COP parameter ε_T) for some BRP heat pump in compliance with the EN 255 standard (at configuration of input temperature of heat-carrier fluid/output temperature of heating water, typically 0/35 °C and 0/50 °C). [7]

Fig. 13b five circulation pumps, used for primary circuit of the BRP heat pumps [7]

The Nova aula building's heat loss (i. e. useful heat power ensuring heat comfort here, when ambient air temperature equals to –15 °C) is approximately 1200 kW. At mentioned 700 kW total power (i. e. 58 % of heat loss), the BRP heat pumps ensure 82 – 85 % of heat supply for this building during average year. [7]

The BRP heat pumps ensure heat supply for:

- air-conditioning (AC) – warn air-heating system (circa 79 % of heat supply, 909 kW heat input, 80/60 °C temperature gradient),
- central heating (CH) – heated floor and space heaters (circa 20 % of heat supply, 250 kW heat input, 55/45 °C temperature gradient),
- preparation of hot service water – insignificant (less than 1 % of heat supply, 55/45 °C temperature gradient).

This system for borehole temperature measurement, monitoring and systematic archivation, used for heat pumps, was started on 1st September 2007.

B. *The Small Research Polygon (SRP)*

The SRP is mainly determined for regenerative and accumulative behaviour of the rocks near energy-exploited boreholes, used for small-business applications, especially for family houses. This polygon is located near the Energy Research Centre building, which is also situated at the district of VSB – TUO, and composed of 9 boreholes and 3 groundwater boreholes:

- 1 core borehole (A) – depth of 160 m, 17 temperature sensors, and distance between them is 10 m (constructed in 2008),
- 1 testing borehole (C1) – depth of 140 m, 15 temperature sensors, and distance between them is 10 m (constructed in 2008),
- 4 monitoring boreholes (C2, E1, E2, E3) – depth of 140 m, 8 temperature sensors, and distance between them is 20 m,
- 2 technological boreholes (TC1, TC2) – depth of 140 m, input line includes 2 temperature sensors in depths of 20 m and 100 m; output line includes 4 temperature sensors in depths of 20 m, 50 m, 100 m, and 140 m; these boreholes are connected to 2 Swedish compressor-based heat pumps (type of IVT Greenline E11 Plus), located at a junction exchange station (part of the Energy Research Centre building),
- 1 experimental borehole (PV) – depth of 20 m, 29 digital temperature sensors (type of Dallas DS18B20, TO92 case), sensor distances is from 0.25 m till 1.00 m, depending on their depth, and 40 analogue temperature sensors (type of PT1000),
- 3 groundwater boreholes (B1, B2, D) – underground water level and temperature measurement.

All the SRP boreholes, except the experimental borehole and groundwater ones, contain an analogue type of resistance sensors PT1000 for temperature measurement with 4-wire connection (i. e. “Sensor+”, “Sense+”, “Sensor-“, and “GND” wires).

The TC1 borehole is very important, whereas its surrounding boreholes (except the PV borehole) form two spiral diagrams, e. g.:

- the first diagram includes the boreholes of E2, D, B1, and C2,
- the second diagram includes the boreholes of B2, E3, A, and E1.

A purpose of this layout configuration, shown in Fig. 14, is to investigate, how various distances among boreholes (and between the TC1 borehole and its surrounding ones) influence some behaviour of these geothermal systems, e. g. some temperature profile analysis of each SRP borehole. These distance values among them are very important parameters for mentioned analysis, modelling, and simulation of thermal conditions and system relationships.

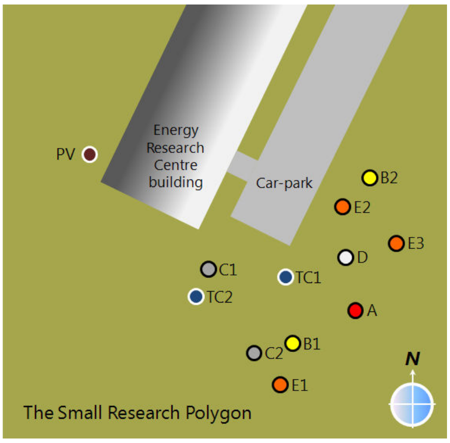

Fig. 14 layout configuration of SRP boreholes with locations of the Energy Research Centre building, car-park, and with their labels

C. *Description of BRP measurement and monitoring system*

The BRP temperatures are acquired by ICP DAS I/O system. Generally, there are about 80 temperature values from 15 boreholes, which are measured via 20 pieces of 4-channel RTD Input Modules with 16-bit A/D converters. These modules are consequently consolidated to measured units (each of 8 modules). Block scheme of BRP measurement system is shown in Fig. 15a.

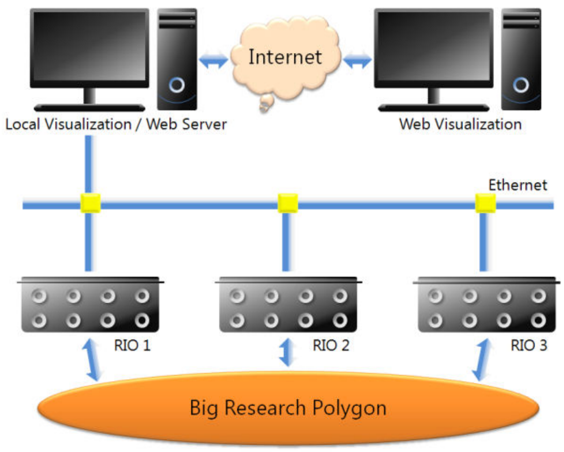

Fig. 15a block scheme of BRP measurement system – real technology of research polygon, remote I/O units, some PCs with local visualization, Web server, and Web visualization

Acquired data are transmitted via the Ethernet from junction wells to machine-room with 10 BRP heat pumps. There is some local PC application, that reads and displays measured values from remote I/O units (RIO modules) and is realized via HMI/SCADA system of Microsys Promotic. Data connection between RIO units and PC is realized via OPC. This local visualization enables to manage user's rights, analyze alarm states, provide temperature historical trends, set graph limits, view acquired data in tables, or save data into some database system. In this case, the BRP heat pumps are also controlled and monitored by system of ProCop Monitor (see Fig. 15b), which acquires all the quantity values and stores data into database system [7].

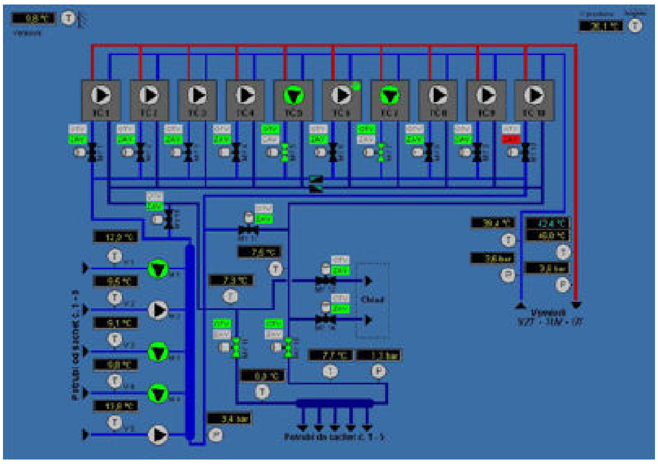

Fig. 15b ProCop Monitor visualization screen of the BRP heat pumps operation and technology temperatures [7]

Temperatures from the BRP are acquired at given time intervals, which can be set from 10 seconds to 1 day (i. e. 86400 seconds). Some temperature changes in rock massif are very slow, so temperature measurement could be also slow.

At the Nova aula building there are not only conference rooms, but also some offices. Although, a control system for this building is able to be autonomous, it is required to consider some utilization of conference rooms for economically sophisticated operation, because exploitation rate and mode are very variable, so required air change with subsequent heat for air-conditioning is very different. This situation is graphically represented in Fig. 16, where Friday and week-end (i. e. Saturday and Sunday) are the last 3 days.

In compliance with projected heat characteristics (i. e. current heat power requirements, provision of required temperature gradient for air-conditioning), system of the BRP heat pumps could not be capable of so-called univalent operation. Ambient air temperature did not fall below –10 °C (in the long term) from 2007 to 2009, so it was not possible to make sure of bivalent point temperature. Haymaking was at the beginning of year 2010, when some congress was held from 24th January 2010 to 27th January 2010. As evidenced by graphical characteristics shown in Fig. 16, during this period the system of the BRP heat pumps enabled to supply desired heat at temperatures less than –15 °C. Five or six BRP heat

TABLE II
VALUES OF INPUT TEMPERATURE OF HEATING WATER, OUTPUT TEMPERATURE OF HEATING WATER, AND THEIR DIFFERENCE IN DEPENDENCE ON APPLIANCE KIND

Kind of appliance	$T_{HW(O)}$[°C]/$T_{HW(I)}$ [°C]	$T_{HW(O)} - T_{HW(I)}$ [°C]
air-conditioning	48.10/43.32	4.78
central heating	49.30/38.43	10.87

Meaning of used SI units; °C = Celsius degree.

pumps usually operate at full capacity; seven HPs for one hour period. Maximum value of heat power $Q_{HT[W]} = P_{HT}$ equalled to 400 kW on 27th January (see Fig. 16).

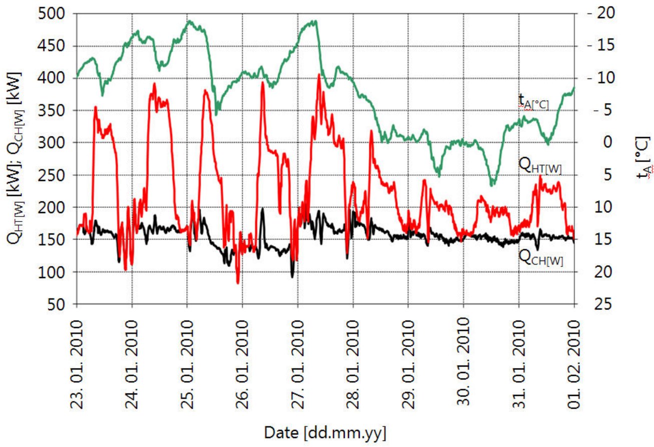

Fig. 16 graphical characteristics of total heat power $Q_{HT[W]}$ (air-conditioning and central heating; red line), heat power for central heating $Q_{CH[W]}$ (central heating; black line), and ambient air temperature $t_{A[°C]}$ (grey line) the BRP heat pumps at extreme conditions (January 2010/February 2010)

Heat power for air-conditioning $Q_{AC[W]}$ is given by division between $Q_{HT[W]}$ and $Q_{CH[W]}$.

This observation adverts to the fact, that putting heat pumps on heating of large buildings with variable operation mode has some specifics in comparison with common buildings (i. e. residential buildings or office buildings). Primarily, it is required to design heat power of HPs so that it appears not only from real presumptions of sub-appliances exploitation, but also it is not unnecessarily overdesigned. In the case of heat pumps, absolute increase of capital expenditure (at power raise of heat source) is higher than in the case of heat exchanger for central heat supply. We could achieve better possibilities for some optimization of resources, if a building project already is designed for heating-and-ventilating utilization of HPs at the beginning. On the other hand, this often is impossible due to project development length, frequency of investment grant scheduling and grants acquisition uncertainty, if an investor does not meant to dig down the full-project. It is also required to take account of "enlightened" service, because an ordinary control system is not fully able to afflict some mode-variability exploitation. [6]

In year 2009, heat supply was 1636 GJ (i. e. 454480.8 kWh; 17 % of this for air-conditioning and 83 % of this for central heating) at electric power consumption equalled to 170950.0 kWh. Resultant value of COP parameter is equalled to

$$\varepsilon_T \Rightarrow \frac{Q_{HT[J]}}{A_{[J]}} = \frac{1636 \cdot 10^9}{170950 \cdot 3.6 \cdot 10^6} \cong 2.658\,. \tag{12}$$

In the first quarter of year 2009 (i. e. January 2009, February 2009, and March 2009) the value of COP parameter equalled to 2.70. [7]

Table II includes some values of input temperature of heating water $T_{HW(I)}$, output temperature of heating water $T_{HW(O)}$, and their difference in dependence on appliance kind (i . e. air-conditioning and central heating). Central heating has greater input temperature and its difference in comparison with air-conditioning. COP parameter value is better, if output temperature of heating water is lower, because the COP parameter value is directly proportional to temperature difference – see (13). So central heating is more advantageous. [7]

If we want to reach better exploitation of the BRP heat pumps, then we disconnect a specific borehole circuit and let the BRP boreholes regenerate. These boreholes can be switched among yourselves, because borehole temperature gradually decreases. Each circuit is usually used for one week (i. e. 7 days). If it is technically possible and financially acceptable, then exchangers could be gently overdesigned. Usage of more boreholes is more expensive, but heat pump will gain more energy from rock massif and its operation will be cheaper. If some heat pump (taking heat from borehole) is available, we can make use of a cold inside borehole to cool some building (e. g. the Nova aula building) in the summer. [7]

D. *Description of SRP measurement and monitoring system*

This system is based on a programmable logic controller (PLC, type of Bernecker&Rainer X20 CP1484), which acquires and processes data from:

- temperature sensors – temperatures of SRP boreholes and heat pump (type of SENSIT TR 026B-37; PT1000/A),
- pressure sensors – measurements of gauge pressures (types of QBE9101-P10U, QBE9101-P60U), and differential pressures (types of QBE63-DP05 and SITRANS P D-76181),
- flow-meters – multi-quantity measurement (i. e. mass-flow, density, sensor temperature, volume-flow, and totalizer mass) – 3 pieces of ultrasonic sensors (type of SITRANS MASS 2100 DI 25) with 3 PROFIBUS DP transmitters (type of SITRANS MASS 6000 IP67 Compact),
- power-meters – measurements of electric supplies of SRP heat pumps (3-phase system, 4-wire connection, and non-symmetric load) – 2 pieces of measurement converters of watt power (type of WEIGEL VUW 2.2).

Most of sensors have linear outputs of current (4-20 mA_{DC}; pressure sensors, power-meters) and voltage (0-10 V_{DC}, pressure sensors), so real values of relevant quantities are calculated via conversion linear equations in dependence on quantity range.

Block scheme of SRP measurement system is shown in Fig. 17. The total number of measured quantities is 150 (with inclusion of a timestamp), which are stored into 2 CSV (i. e. Comma Separated Values) files:

- temperatures.csv – currently measured data from the SRP boreholes (106 temperature values), the SRP heat pumps (12 temperatures from pair sensors, 4 values of pressure), and flow-meters (27 values). For better orientation in this file, there is also a header. These values are re-written every 10 minutes, whereas created file is used for online visualization,
- year_month.csv – acquired data are stored with one-minute period, whereas created file is used for offline statistical analysis (e. g. hour, day, or month temperature means). Every month a new file is created with specific filename (e. g. “2010_5” filename corresponds to May 2010 etc.).

The data files contain some borehole identification code (e. g. “PV1_75” label corresponds to the experimental borehole in a depth of 1.75 m) and a timestamp of each measurement.

Table III includes some electric and non-electric quantities, which are used for COP parameter calculation of SRP heat pumps, and saved to CSV measurement file (temperatures.csv) for Web visualization, available at http://trt.vsb.cz.

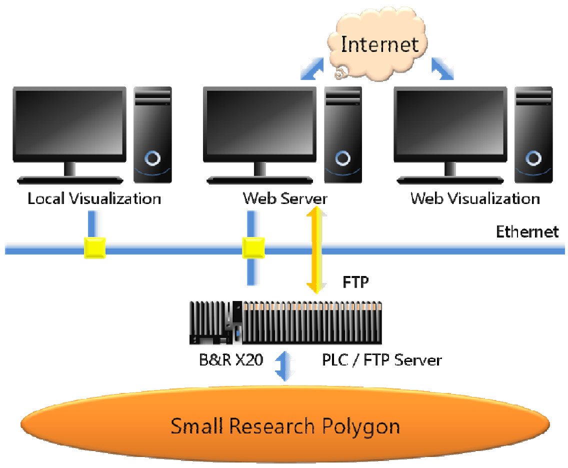

Fig. 17 block scheme of SRP measurement system – real technology of research polygon, PLC of B&R X20 CP1484, some PCs with local visualization, Web server, and Web visualization

Following example illustrates, what quantities, mentioned in Table III, are important for simple calculation of the ECOP parameter value based on energy flows, whereas an equation form is identical with (2), i. e. power form, see (13).

$$\varepsilon_T \Rightarrow \frac{Q_{HT[W]}}{A_{[W]}} = \frac{P_{HT}}{P_{EL}} = \frac{M_{HW} \cdot c_{HW} \cdot \left[T_{HW(O)} - T_{HW(I)}\right]}{P_{EL}}. \quad (13)$$

A numerator of (12) represents so-called thermal power quantity inside HP output circuit of heat pump for the TC1 borehole (it is preferred) or the TC2 borehole, because heat pump for the TC1 borehole includes sensors for measurement of temperature difference of heat water (naturally in kelvins or Celsius degrees), i. e. $T_{HW(O)} - T_{HW(I)}$. Of course, it can be measured by SITRANS flow-meter, located inside HP output circuit. For more detailed analysis of thermal system′, it is essential to set pressure ratios and gradients. Basic measured characteristic is a pressure dependence on heat pump I/O (in front of compressor and behind compressor) in relation to I/O temperatures [12].

For calculation of the ECOP parameter value, let us consider these quantity values with a timestamp (4th July 2010, 6:50 AM), i. e. M_{HW} = 0.5802 kg · s^{-1}, c_{HW} = 4179.6 J · kg^{-1} · °C^{-1}, $T_{HW(I)}$ = 39.90 °C, $T_{HW(O)}$ = 43.56 °C, P_{EL} = 2875.8 W, then momentary value of ECOP parameter is equalled to

$$\varepsilon_T = \frac{0.5802 \cdot 4179.6 \cdot \left[43.56 - 39.90\right]}{2875.8} \cong 3.086 . \quad (14)$$

A producer of IVT Greenline E11 Plus compressor-based heat pump (powered by electric motor) type informers, that the value of ECOP parameter equals to 5.023 (at 0/35 °C configuration), if you like 3.483 (at 0/50 °C configuration).

TABLE III
LOGGED ELECTRIC AND NON-ELECTRIC QUANTITIES USED FOR COP PARAMETER CALCULATION OF SRP HEAT PUMPS, AND WEB VISUALIZATION

Symbol	Quantity	Unit
$P_{E(G)}$	gauge pressure before evaporator	kPa = 10^3 Pa
$P_{E(D)}$	differential pressure of evaporator	kPa = 10^3 Pa
$P_{C(G)}$	gauge pressure before condenser	kPa = 10^3 Pa
$P_{C(D)}$	differential pressure of condenser	kPa = 10^3 Pa
$T_{FMA(O)}$	temperature of anti-freeze mixture (from the TC1 borehole)	°C
$T_{FMA(I)}$	temperature of anti-freeze mixture (to the TC1 borehole)	°C
$T_{FMB(O)}$	temperature of anti-freeze mixture (from the TC2 borehole)	°C
$T_{FMB(I)}$	temperature of anti-freeze mixture (to the TC2 borehole)	°C
$T_{HW(O)}$	temperature of heating water (from borehole)	°C
$T_{HW(I)}$	temperature of heating water (to borehole)	°C
$T_{C(I)}$	temperature of condenser input	°C
$T_{C(O)}$	temperature of condenser output	°C
$T_{E(I)}$	temperature of evaporator input	°C
$T_{E(O)}$	temperature of evaporator output	°C
M_{FMA}	mass-flow of anti-freeze mixture (for the TC1 borehole)	kg·s^{-1}
M_{FMB}	mass-flow of anti-freeze mixture (for the TC2 borehole)	kg·s^{-1}
M_{HW}	mass-flow of heating water	kg·s^{-1}
P_{ELA}	electric supply of heat pump (for the TC1 borehole)	kW = 10^3 W
P_{ELB}	electric supply of heat pump (for the TC2 borehole)	kW = 10^3 W

Meaning of used SI units; kg = kilogram, s = second, Pa = pascal; °C = Celsius degree, W = watt.

VI. CONCLUSION

There are two fundamental parts in this paper, i. e. theoretical part (effectiveness evaluation), and practical part (monitoring of COP parameter).

The first fundamental part is mainly focused on evaluation of energy effectiveness of heat pumps, whereas it is required to appear from the various kinds of COP parameters – direct (DCOPs, i. e. ICOP and ECOP parameters), exergy (ExCOPs), and primary COPs – to correctly compare effectiveness of various kinds of heat pumps, whereas there is a comparison of DCOPs for compressor-based HPs and absorption HPs only. There are also some words about exergy analysis – with mathematic equations, based on (1) – and some macroeconomic analysis for effectiveness of HPs.

The second fundamental part is focused on monitoring of DCOP parameter value of compressor-based heat pumps powered by electric motor (its balance diagram is mentioned in the first part of this paper), located at the district of the Small Research Polygon. There are some descriptions of the BRP, the SRP, and monitoring of the quantities used for the ECOP parameter value calculation (ECOP definition is mentioned in the first part of this paper), based on energy flows. The result of this simple calculation conforms to producer's value of ECOP parameter. In the case of the BRP, importance of COP parameter is discussed at real heating ways and means of the Nova aula building.

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