Operating Characteristics of Multivalent Systems Using Renewable Energy Sources

Petr Mastny, Lukas Radil, and Zuzana Mastna

***Abstract*—**Software support for simulations and evaluation of energy systems operating states in modern low-energy construction has – within specific conditions in the Czech Republic – increasing importance. Multivalent energy systems have the most significant importance for investors. Designs of such systems are – regarding energy and economy balance – very demanding and therefore there have been by the project engineers set requirements to assemble knowledge base in this field. In the paper there are explained possibilities of usage of thermal processes mathematical modeling in Mathematica® software environment for design and analysis of operating characteristics of multivalent thermal systems using renewable power sources. Each step of mathematical description of thermal system – including heat pump, solar and accumulation system – comes from the real measuring on physical model of heat pump. The results of mathematical simulation are compared with results of energy analysis on physical model of combined system.

***Keywords*—**Heat Accumulator, Heat Pump, Mathematical Modelling, Renewable Energy, Multivalent System.

I. Introduction

IN the past few years, more and more discussions on power sources for low energy buildings are held. Therefore bivalent and multivalent energy systems come to fore, but experience with the design and operation are little. One of the factors that influence the development of this issue is the reluctance (and sometimes even ignorance) to install new systems. Regarding information given above, it was required to specify the procedures and conditions for designing combined systems in the municipal building construction with an emphasis on energy and economic justification of the designed systems. In terms of energy balance there is for a residential building decisive the amount of energy needed for heating and hot water. This is influenced by the fact that to cover the requirements for heating and hot water is from the total energy consumed up to 80%. The remaining part of the energy is consumed in common operation of house. The most commonly used alternative sources of energy in our conditions are solar systems and heat pumps. The design of a functional energy system itself is a complex process. The definition of the mutual linkages between the various components must be based on physical principles. The primary objective of the energy system is to provide all the energy needs of the building. For applications with alternative sources of energy such as solar systems or heat pumps, it is very important to ensure that project design have already attended to the mutual links between energy source and used building materials, which has a considerable influence on the building's energy.

Based on experience in the design of energy systems has been compiled the taxonomy of mutual relations between different parts of the energy system and building. For the compilation there is used the "IS A" and "HAS A" association. This association links do not describe all the interactions between different parts of the system, but can serve as basic information on the procedures for the design of the energy system. Compiled taxonomic diagram is shown in Fig. 1.

The taxonomy shown in Fig. 1 does not form a comprehensive representation of all mutual relations; it is an example of the main idea how to demonstrate the first step in knowledge modeling. Taxonomy in this form is giving specific answers to questions like “What is it“, “What is it a part of”, etc. For instance, the question -" What is a heat pump "- you can easily find the association that heat pump is a heat source and it is a part of heating system. And in a similar way we can continue to define further relations and constraints (Fig. 2).

Determination of interactions between components of the energy system and the building is the starting point for designing the power system. At the CRURES (*Center for Research and Utilization of Renewable Energy Sources*) research workplace there were based on the compiled taxonomy of relations developed mathematical models for determining operating parameters of alternative energy sources. In the following passages there will be described the mathematical framework for the validation of the heat pump in the power system and there will be presented the results of

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P. Mastny is with the Brno University of Technology, Centre of Research and Utilization of Renewable Energy Sources, Faculty of Electrical Engineering and Communication, Technicka 3058/10, 616 00 Brno, Czech Republic (phone number: +420 541149230; e-mail: mastny@feec.vutbr.cz).

L. Radil is with the Brno University of Technology, Department of Electrical Power Engineering, Faculty of Electrical Engineering and Communication, Technicka 3058/10, 616 00 Brno, Czech Republic (phone number: +420 541149285; e-mail: lukas.radil@phd.feec.vutbr.cz).

Z. Mastna is with the Brno University of Technology, Department of Building Services, Faculty of Civil Engineering, Veveri 331/95, 602 00 Brno, Czech Republic (phone number: +420 541147406; e-mail: mastna.z@fce.vutbr.cz).

the analysis on combined energy system consisting of a heat pump and solar system.

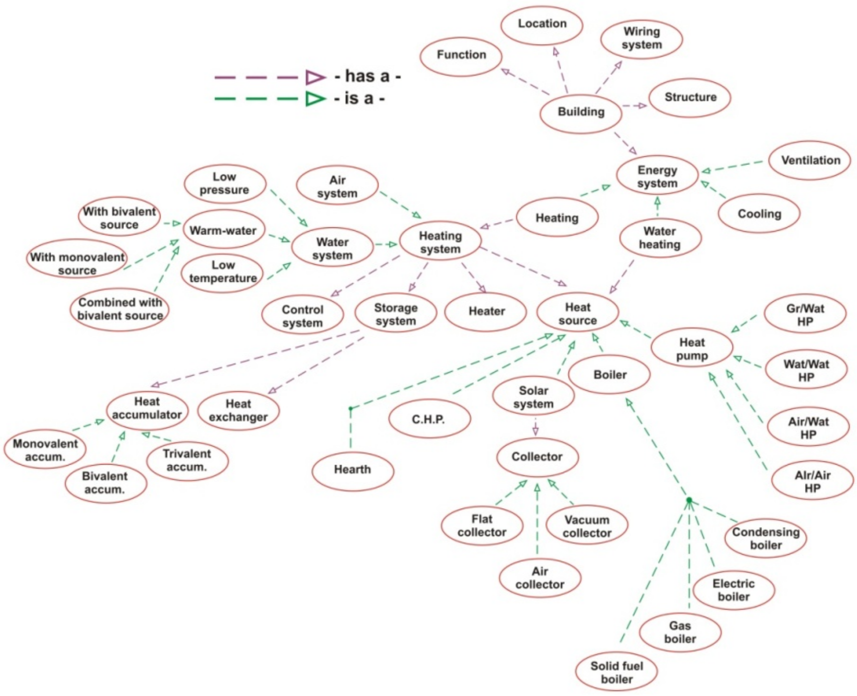


Fig. 1 Taxonomy of basic classes related with the design of energy system [1]

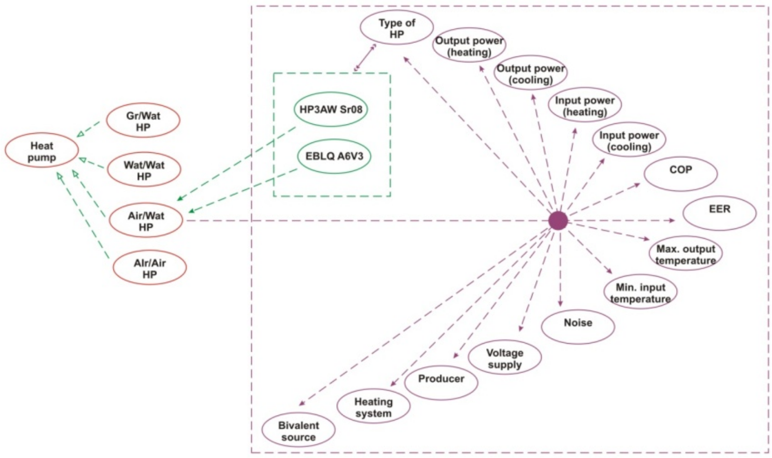


Fig. 2 Assigning characteristics to individual system components [1]

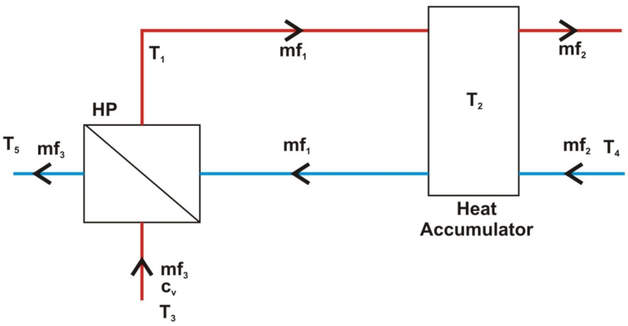
II. Heat Pumps in Energy Systems

Heat pumps are used increasingly, and their applicability in the energy market is considered high. The number of installed heat pumps in the Czech Republic since 1993 till present is constantly growing. Last year (2010) there were installed nearly 4.000 units of heat pumps with total performance of approximately 60 MW.

Systems with heat pump are regarding operating characteristics very specific. The heat pump as an energy source using low-potential heat exchangers can be operated in two basic circuits [2]. The first option is to run heat pump as a monovalent power source, but this option is in terms of energy efficiency less suitable. The reason for this finding is the fact that such system with a heat pump is due to the high installed performance of heat pump working in optimal mode for a very short period of time during the year. Other possible use of heat pumps in the energy system is so called bivalent (multivalent) connection. In this system, the involvement of the heat pump is supplemented by another (bivalent) source, which may be e.g. solar system, electric power boiler, etc. The thermal performance of heat pump is in the multivalent system designed to cover approximately 60% of total heat loss of the building. The remaining part of the required energy is supplied by an auxiliary energy source, which involvement due to the heat pump can be parallel or alternatively parallel [2], [3].

A. *Mathematical Simulation of Operation Characteristics of Heat Pump*

To obtain information about physical processes during operation of heat pump there is for the mathematical simulation selected connection shown in Fig. 3. In this energy scheme heat pump will be intermittently switched (simulation of operational cycles), and will supply hot water to the accumulation tank which will supply the heating system of building.



mf – mass flow, T_1 – output temperature of HP, T_2 – temperature in heat accumulator, T_4 – heating system output temperature, T_3 – air input temperature, T_5 – air output temperature, c_v – air specific thermal capacity

Fig. 3 Basic application of air-to-water heat pump for simulation of operation characteristics

Analysis of operating states is developed in the programming environment of Wolfram Mathematica® and as starting data there are used real operational values obtained from measuring on the operand multivalent thermal energy system. Performed mathematical simulations of operation of the assembled power system (Fig. 3) should give an answer to the question, what value will reach COP of heat pump during the entire heating season. The basic argument for such an evaluation is the assumption that the drop in temperature in the accumulation tank must be kept within defined limits.

For the simulation the operating characteristics of the system there are compiled mathematical equations describing the physical processes in the thermal system. Equation (1) - (5) describe these physical processes:

- equation (1) describes the equality of the output temperature at the outlet of the heat pump and heating power (Q_{TP}) of the heat pump, "k" to determine the state of the heat pump (k = 1 – on, k = 0 – off),
- equation (2) describes the heat pump – thermal energy on input together with power supplied (W_{EP}) from the network is equal to the total output energy,
- equation (3) describes the behaviour of the total power supplied to the heating system, depending on the temperature difference T_2 and T_4,
- equation (4) describes the accumulation reservoir – the temperature difference at the input and the output is proportional to the size of the accumulation reservoir (mAc) and to a derivative of output temperature T_2,
- equation (5) describes the heating system – the overall heating power supplied to the heating system is equal to the average value of input temperature T_2 and output temperature of water T_4, room temperature T_{room} and the heating constant k_{heat}.

$$e_1 = mf_1 \cdot c_p \cdot (T_1 - T_2) == k \cdot Q_{TP}[T_1]; \qquad (1)$$

$$e_2 = mf_3 \cdot c_v \cdot (T_3 - T_5) + k_h \cdot W_{EP}[T_1] == mf_1 \cdot c_p \cdot (T_1 - T_2); \qquad (2)$$

$$e_3 = mf_2 \cdot c_p \cdot (T_2 - T_4) == Q_{TP}; \qquad (3)$$

$$e_4 = c_p \cdot (mf_1 \cdot (T_1 - T_2) + mf_2 \cdot (T_4 - T_2)) == c_p \cdot mAc \cdot derT_2; \qquad (4)$$

$$e_5 = Q_{TP} == k_{heat} \cdot ((T_4 + T_2)/2 \cdot T_{room}); \qquad (5)$$

A prerequisite for the mathematical modelling is to determine the limiting conditions when the heat pump is in operation and when it is out of operation - definition of heat pump cycles. To solve the assembled differential equations there is used Runge-Kutt numerical method.

So far there has not been mentioned that the basic operational indicator of the heat pump is the *coefficient of performance* (COP). COP is defined as the ratio of the obtained heat Q_{TP} (heating capacity) and the energy required for heat re-pumping W_{EP}. It expresses how many times we get more energy than in the form of drive energy (electricity) we put in. Based on the available values of COP of the existing heat pump there is defined dependence of COP defined on outlet temperature of the heat pump [7], [2].

After determining the operating parameters of a heat pump, such as thermal power and electric input, there can be easily programmed the functions to define the average energy heating factor. To determine COP_{ave} there is used equation (1), thus the ratio of heat performance of the heat pump and the energy supplied to drive the pump [8].

At the beginning of the script there is at first determined the behaviour of the heating factor depending on the input temperatures using already known values of heat performance and amount of supplied electrical energy. Fragment of compiled script looks as follows:

```
datFactor=<<"datCOP";
Qtp[Date_]=datFactor[[1]];
dat=datFactor[[1]];
eps[Date_]=Interpolation[dat][Date];
Plot[{eps[Date],0},{Date,dat[[1,1]],
dat[[-1,1]]},AxesLabel->{"T_air(°C)",
"COP(-)"},PlotStyle->
{{Hue[0.63],Thickness[0.008]},{GrayLevel[0],
Thickness[0.001]}}]
```

The output of the script is a graphical representation of the heating factor depending on the input temperature of the heat pump, which is shown in Fig. 4.

Determination of the heating period duration in the Czech Republic and temperature fluctuations during the year is based on long–term measurements during the years 1997–2009.

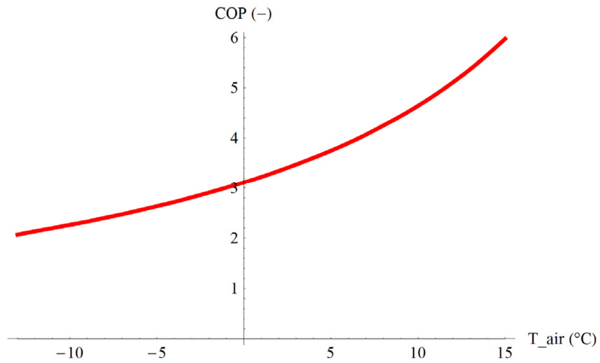


Fig. 4 Behaviour of COP for simulated values of HP

There was compiled a computational script which allows to process the input values in graphic form – the script itself is shown below in the text. Environmental outdoor temperature, at which the heat pump starts to work, is used *toutheat* = 13°C.

```
TemperatureData={{1,-2.7},{2,-1.1},{3,2.2},
{4,8.4},{5,13.8},{6,16.9},{7,18.2},{8,17.7},
{9,12.7},{10,7.6},{11,2.7},{12,-1.5},
{13,-2.7}};
helpfce[month_]=Interpolation[TemperatureData
[month];
Temperature[m_]:=helpfce[m]/;1≤m<13;
Temperature[m_]:=Temperature[m-12]/;m≥13;
Temperature[m_]:=Temperature[m+12]/;m<1;
teplsechlp[t_]:=Temperature[t/(30.417*24*3600)];
year=12*30.417*24*3600;
strhodn=1/year NIntegrate[teplsechlp[t],{t,0,year}];
zadstrhodn=6.8;
teplsec[t_]:=teplsechlp[t]-strhodn+zadstrhodn

toutheat=13;
Plot[{teplsec[t],toutheat},{t,0,2*12*30.417*24*3600}
,AxesLabel->{"t    (s)","T_air    (°C)"},PlotLabel->"
Temperature    during    the    year",    PlotStyle->
{{Thickness[0.01`],GrayLevel[0]},
{Thickness[0.01`],RGBColor[1,0,0]}}]
timeheatstart=t/.
FindRoot[teplsec[t]==toutheat,{t,2×10^7,3.5× 10^7}];
timeheatend=t/.
FindRoot[teplsec[t]==toutheat,{t,4×10^7,5× 10^7}];
Tx=(timeheatstart/(3600*24))/30.417;
Ty=((timeheatend/(3600*24))-365)/30.417;
Print["Start  of  heating  season  =   ",  Round[Tx],".
month"]
Print["End  of  heating  season  =   ",  Round[Ty],".
month"]
```

In the Fig. 5 there is marked the period during which is in a given locality running the heating season. The length of the heating season is given by the outdoor temperature values during a year and by defined environmental temperature *toutheat* at which the heat pump starts to operate. The whole simulation was proceeded for parameter of required temperature in the accumulation reservoir $T_2 = 45°C$.

As it can be seen in the Fig. 5, the heating season begins in September and ends in May, as it is also shown in the print-out of the script below Fig. 5.

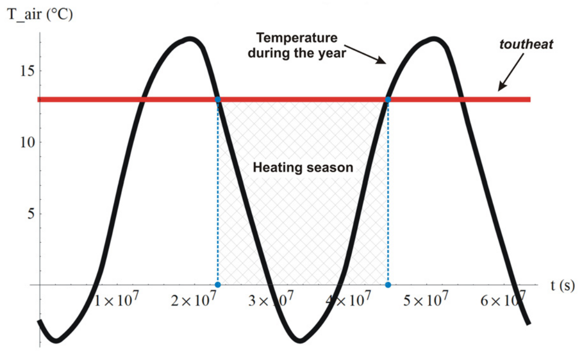


Fig. 5 Behaviour of temperatures during year – determinative of heating period

```
[Out]=
Start of heating season = 9. month
End of heating season = 5. month
```

The next step is to determine the total thermal energy needed for heating (*energyforheating* - Q_{TP}), then the total amount of electric energy needed to drive the heat pump during the heating season (*electricenergyforheating* - W_{EP}) and the average energy heating factor (COP_{ave}) of a heat pump during the heating season. These calculations are presented in the script by the following command sequence:

```
energyforheating=NIntegrate[Qtp[teplsec[t]],
{t,timeheatstart,timeheatend}];
Print["Heat consumption =   ", energyforheating/10^9,"
(GJ)"]

electricenergyforheating=NIntegrate[Qtp[teplsec[t]]/
eps[teplsec[t]],{t,timeheatstart,timeheatend}];
Print["Power consumption =   ",
electricenergyforheating/10^9,"  (GJ)"]

Print["COP_ave =  ", NumberForm
[energyforheating/electricenergyforheating,3]," (-
)"]
```

The following step is to determine the total heat energy required for heating (Q_{TP}), determination of the total amount of electricity needed to drive the heat pump (W_{EP}) and the calculation of mean energy coefficient of performance (COP_{ave}) of heat pump. The result of the simulation is shown in Fig. 6 and Fig. 7. The resulting characteristics clearly define the operation characteristics of the heat pump. In the picture below there can be noticed the dependence of COP on the ratio of the produced heat energy to supplied electricity.

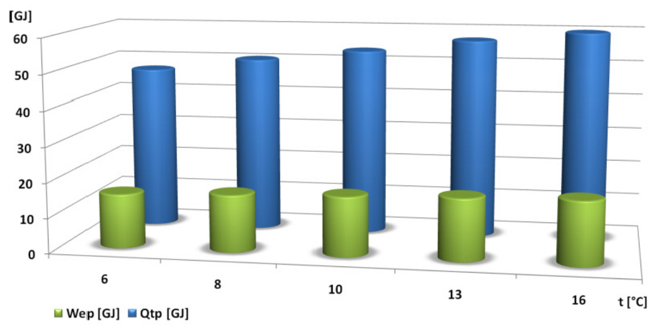


Fig. 6

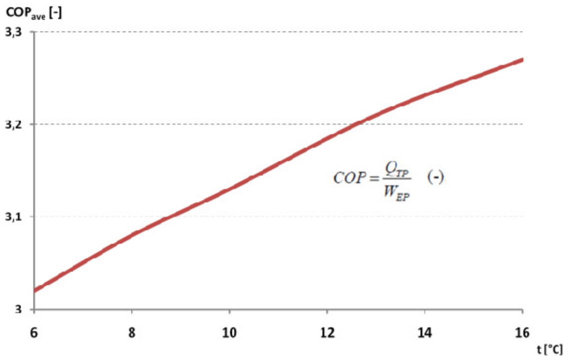


Fig. 7

Results obtained from simulations were compared with final analysis of data obtained from measuring on the physical model of heat pump. Comparing the results of mathematical modeling of energy system with a heat pump with a real physical model is necessary to verify the validity of hypotheses under consideration and to confirm whether this algorithm can be used to design such systems in different locations regarding local climatic conditions.

B. Mathematical Description of Heat Accumulator

The accumulation systems are used to heat accumulation and subsequent distribution of the accumulated heat. Its structure is variable. From simple forms with one heat exchanger to the hybrid tanks combining several heat exchangers. Currently, as a storage medium there is mostly used liquid water, in future there is a perspective counting with the application of substances with a phase change.

In a hybrid system (heat accumulator with solar panels and independent heat pump) there is a storage container with associated media very important part of the combined system. Generally speaking, the accumulation systems, but mainly the heat-transfer agents, are subjected to high requirements in terms of corrosion resistance, high heat capacity, low thermal expansion, acceptable density and related viscosity.

To simulate the operating conditions there has been chosen an accumulation tank in the shape of cuboid. In this case there is water used as an accumulation substance. The actual accumulation tank, which has been subsequently tested in connection with combined heat system, is shown in Fig. 8.

From the measured data of water input and output temperatures there are compiled the regression curves of heating model. Using mathematical modelling there has been generated area, which corresponds to the amount of accumulated heat during monitored time unit (Fig. 9). During the simulation there is not re-examined the initial container temperature, hence the result of simulation is the speed of start and time of stabilization of the storage medium temperature. Transition states during the accumulation of thermal energy (red dashed curve) are caused by opening and closing the thermostatic valve.

Fig. 8

Behaviour of the start speed and time of temperature stabilization in the storage tank are in simulation characterized by polynomial function (equation 6). Similarly there is described temperature behaviour in the storage tank after stabilization (equation 7). It is assumed that the input temperature curve in the system is linear (equation 8). For the determination of the quantity of accumulated heat there has been used integration according to the equation (9). Simulation of heat transfer in the heat storage tank is based on volumetric flow of heat transfer medium through the pump Q_v = 0.4 $l.s^{-1}$, water density ρ = 985.2 kg m^{-3}, specific heat capacity of water c = 4180 $J.kg^{-1}.K^{-1}$ and from equation (10) which expresses the amount of accumulated heat.

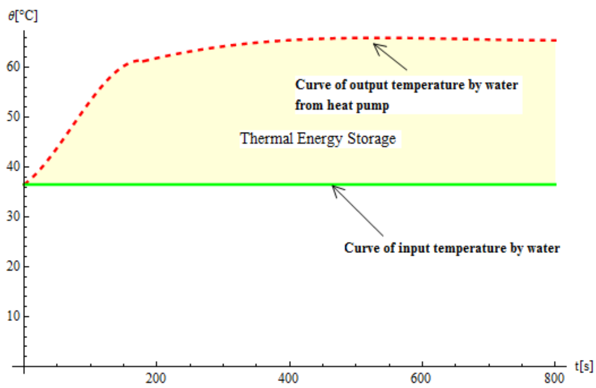


Fig. 9

$$f[x] == n_1 + n_2^x + ... + n_i^x \quad (6)$$

$$g[x] == n_1 + n_2^x + ... + n_i^x \quad (7)$$

$$h[x] == a \cdot x \quad (8)$$

$$a = \int_{x1}^{x2} f[x]dx + \int_{x2}^{x} g[x]dx - \int_{x1}^{x} h[x]dx \quad (9)$$

$$Q = V \cdot \rho \cdot c \cdot_{\Delta} \Theta \qquad (J) \quad (10)$$

III. ANALYSIS OF OPERATING DATA OF HEAT PUMP PHYSICAL MODEL

The above described mathematical models of the combined heating system has been used as a basis to assemble a physical model, on which are then analyzed various operating conditions, and consequently there are obtained data compared with results of mathematical modelling. Technological scheme of the physical model can be seen in Fig. 10. In the Fig. 11 there is shown the secondary part of the assembled system. On the assembled model there are measured operating characteristics and these are compared with the results of simulations.

A. Description of the Measuring System

The data being measured is transferred, using a separating multiplexer, from nine sensors into a measuring system formed by the NI−6023E plug-in card. Signals from all the measuring sensors are conveyed in a defined time loop to the analog inputs of the measuring card. The card will digitize this data and forward the rough data to the control program (in the Matlab script). This script not only communicates with the measuring card, thus controlling the whole measurement but, in addition, it controls the run of the optimization circuit via the digital outputs of the card. To enable the data to be archived in a clear way and to be further processed, the data is sent by the script to the MySQL database on the server, and the whole loop is repeated. The data held in the database can be further processed independently of the measurement in progress, i.e. sorting and additional calculations can be performed. Data modified and prepared in this way can be presented on-line on the Internet practically in real time. More detailed description of each part of measuring system and its control programme is pointed in [11], [12].

B. Resulting Description of the Analysis

The following pictures (Fig. 12 and Fig. 13) show behaviour of the coefficient of performance (COP) and electricity
(W_{EP} – power input) required to drive the heat pump. The behaviour of the COP is presented in response to change of the heat transfer fluid input temperature to heat pump (T_{IN}) and as a parameter of such dependence there is used the output temperature of the heat pump (T_{OUT}). In a similar manner there is also evaluated power dependence of the heat pump (W_{EP}), which is part of the physical model. W_{EP} dependence on the output temperature of the heat pump (T_{OUT}) is shown in Fig. 13. As a parameter there is used the air temperature in the vicinity of the heat pump ($T_{IN\text{-}AIR}$). Even with this dependence there can be seen that the real physical model in terms of operating characteristics behave similarly, as assembled mathematical model.

In the context of comparative analysis of the results of mathematical simulation on mathematical model of the combined system there can be stated that the results of this simulation conform to real operational characteristics of the heat pump. Chosen mathematical description is useful for initial evaluation of the characteristics of the combined system regarding its practical application.

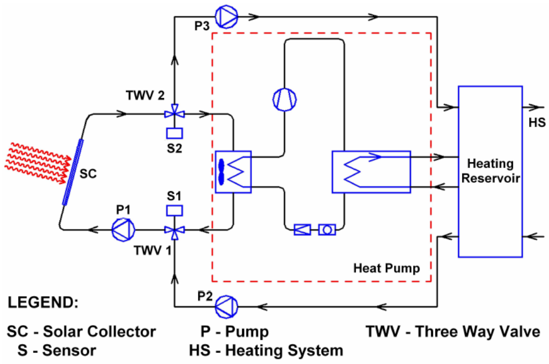


Fig. 10

Fig. 11

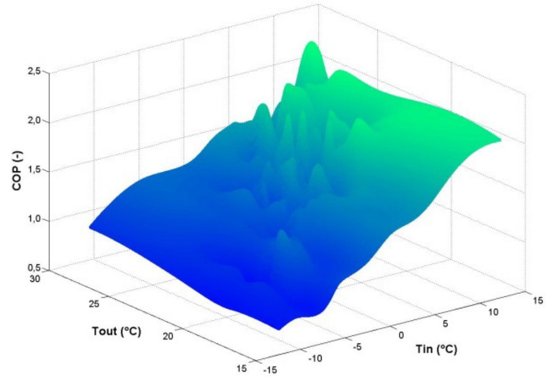


Fig. 12

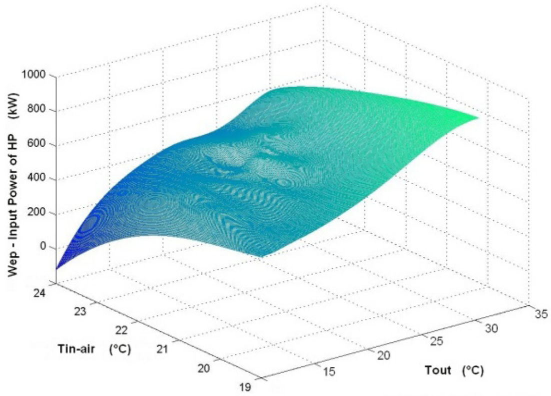


Fig. 13

On the physical model there were also analyzed other parameters such as pressure ratios, thermal performance of the evaporator and the condenser, coolant flow rate depending on the input and output temperatures, and many others. Next pictures present examples showing some of the analyzed operating parameters.

In the Fig. 14 is the behaviour of compression ratio in relation to input temperature (T_{in}) for the output temperature parameter (T_{out}).

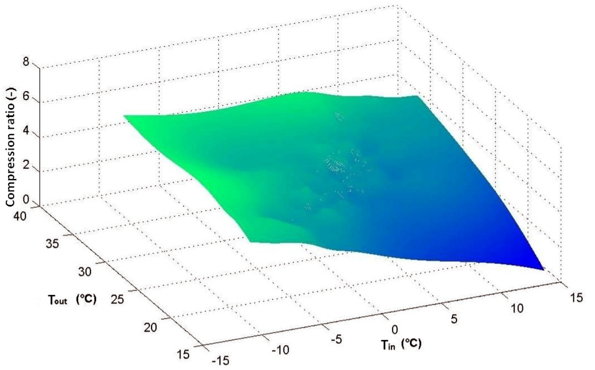


Fig. 14 Compression ratio in relation to input and output temperature

For better understanding there is the behaviour of input and output pressure difference according to the input temperature pointed (see Fig. 15). The Fig. 15 explains that the input and output pressure difference decreases together with increasing input temperature but increases because of growing temperature in heat pump output (T_{out}). This fact means that because of high output temperatures in heat pump the pressure load grows and therefore the service life of used components such as compressor shortens.

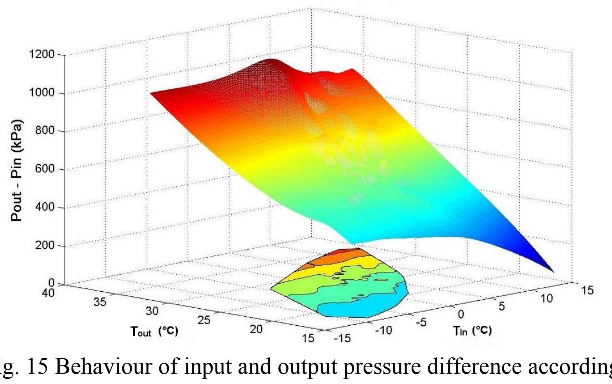


Fig. 15 Behaviour of input and output pressure difference according to the input and output temperature

More detailed analysis of operational parameters of a physical model of heat pump has been published in scientific papers published author in several specialized international conferences and international journals [2], [13].

IV. Conclusion

Designing of energy systems in modern low-energy construction is currently among the actual problems and not just in terms of development of energy sources, but a significant proportion of the expansion of this issue is also economic development in the field of energy management. The effort to maximize the utilization of energy sources and the usage of renewable energy sources leads to realization of combined energy systems. Selected results of the research project "Optimization of the Operation of Cooperating Alternative Power Sources" being solved at Brno University of Technology, described in this article present the results of mathematical modeling and results of physical experiments on the energy systems using alternative power sources. The results of analysis together with practical experience of the authors and research workers at CRURES center were used to compile a knowledge base useful for the design of multivalent power supply systems in low energy buildings.

The results presented in this paper show that mathematical modelling together with the experience of real operation of heating energy systems leads to optimization of energy system design. The advantage of applied simulations is the ability to verify the operational characteristics of the designed energy system and its subsequent optimization. Currently, these procedures are particularly needed with regard to the increasing installation of energy systems using renewable energy sources and that are currently designed as multivalent.

Analysis of the results of the mathematical modelling of operation of energy systems shows that, one assembled energy system will have different operational characteristics when installed in different locations. By comparing the results obtained from mathematical modelling with real values measured on a physical model of the energy system, there can be stated that the chosen mathematical description of the heat pump is very close to the real parameters. Assembled mathematical model is presently used as a support for designing multivalent energy systems for specific objects.

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Petr Mastny was born in 1976. He graduated in Electrical Power engineering in 2000 from Brno University of Technology. His Ph.D. he obtained in October 2006. In December 2010 he has been appointed as Associate Professor at Brno University of Technology.
He has been with Department of Electrical Power Engineering, Brno University of Technology, Czech Republic since 2005. His current position is assistant professor. His field of interest covers the problems of utilization of renewable energy source and questions of energy management systems with renewable energy sources and their influence on environment.
Assoc. Prof. Dr. Petr Mastny has been member of WSEAS (The World Scientific and Engineering Academy and Society) since 2007, member of NAUN since 2009, member of IEEAM since 2010 and member of CIRED since 2009.

Zuzana Mastna was born in 1979. She graduated in Design of Building Structures in 2002 from Brno University of Technology. Her Ph.D. she obtained in May 2010.
She has been with Institute of Building Structures, Brno University of Technology, Czech Republic since 2009 and currently works as a designer and sales agent in a foreign building company (Austria). Her current position in University is assistant professor. Her field of interest is indoor microclimate of buildings.
Dr. Zuzana Mastna has been member of WSEAS and NAUN since 2009.

Lukas Radil was born in 1983. He graduated in Electrical Power engineering in 2008 from Brno University of Technology.
He has been with Department of Electrical Power Engineering, Brno University of Technology, Czech Republic since 2009. His current position in University is technical employee. His field of interest covers the problems of utilization of renewable energy source specially energy storage.