BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

FACULTY OF MAECHANICAL ENGINEERING

MATHEMATICAL MODELING
OF HIGH-CAPACITY HEAT PUMPS

Dissertation Theses

by

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1. The present state of science, the aims of dissertation

Slovakia is extremely poor on fossil fuels. Therefore, the utilizable geothermal potential found in the Košice basin, which is 300 MW (see [14]), is believed to have a strategic importance in Slovakia's energy and environmental policy.

Temperatutre of geothermal energy carrier would according to the initial optimistic prognosis exceed 140 °C. For this reason direct conversion of geothermal energy into power by means of ORC technology was taken into account. Results of economic effectiveness of this plan prove that it is not justified. Costs of power production by means of ORC technology were at that time 3-4 times higher than the average costs in Slovakia. As results of test drilling prove, the temperature of the geothermal energy carrier would not be higher than 130 °C. Abundance of a single production well would be 60 kg/s. Therefore geothermal energy utilization in the District Heating Network seemed to be the most meaningful solution in spite of the 15 km distance between the network and the wells. Thus the idea of geothermal project in Košice was part of part of long-term development of the District Heating Network.

Company TEKO, which is the provider of the heating and power plant in Košice, planned the closure of block TEKO I, which is reaching the end of its life cycle. This could result in a shortfall of 200 MW of heating capacity. Study [18] worked out by company EGÚ Bratislava dealed with the possibility of its replacement. From the three possible variants such a variant was proposed, that would supply the city with 2500 TJ of geothermal energy, while 100 MW of heating capacity could be obtained 8 geothermal doublets. Further 100 MW of heating capacity could be obtained from operating a combined cycle heating and power plant. Since financing establishment of combined cycle heating and power plant was not ensured, life cycle of block TEKO I had been extended. Anyway, geothermal energy utilization still appeared on the agenda.

Danish company Houe & Olsen in cooperation with icelandic company Kvistgaard worked out a business plan (see [13]) of geothermal energy utilization in Košice basin on commission of GEOTERM company. According to this plan significantly more intensive geothermal energy utilization could be realized, that would enable us to supply the city with 2600 TJ geothermal energy from 5 doublets or 2300 TJ geothermal energy from 4 doublets for district heating purposes. The study also states that considering the current stage of preparation as well as the contract signed between companies TEKO and GEOTERM this seems to be realistic in the year 2007 at best. Knowing the local conditions, preparation will be likely delayed.

At that time closure of both block TEKO I and TEKO II with a total power output 120 MW will be actual. According to the planned cut-back, total power output of the Slovak Republic will decrease by 18000 MW by 2010. This makes replacement of the two blocks by a combined cycle heating and power plant probable. Power output of this plant could be significantly higher than the shortfall arising from the closure of the mentioned blocks. However, establishment of this plant will be actual by the beginning of the next decade, when geothermal utilization according to plan [13] will be a reality. Therefore a new philosophy is needed to improve the energy and economical efficiency of the use of geothermal energy.

For this reason a research team of Technical University played a key role in this process. My primary aim was to support this effort and contribute to the concept described in e.g. [9], [10], [20], [21], which assumes that significant progress may be achieved when building up a hybrid combined cycle power plant instead of a usual combined cycle concept. The hybrid concept enables us to feed the low-temperature geothermal heat into the steam cycle by means of feed water preheating. Thus, geothermal energy may be converted to power wuthout applying cost intensive ORC or Kalina cycle. This could lead to an increase in power output for constant fossil fuel consumption or a decrease in fossil fuel consumption for constant power output.

Except cogenerated heat and power production, **cogenerated** use of geothermal resources and natural gas is typical for such a plant as compared to the usual plant, in which their utilization would be **independent**.

Temperature of the returning secondary geothermal energy carrier will change in the range 40-50 °C. Considering its expected mass flow rate, significant heating capacity might be generated.

Since it is not possible to accurately assess the conditions under which heat pump will operate after the project realization, the aim of the presented work was not a decision making in profitability of one or another variant. The main aim of the dissertation was to work out a software module enabling resolving problems connected with heat pump application. These problems were resolved only in such an extent, that would clarify the backround of the main aim of the dissertation. The collaboration with a research group established at the Technical University of Košice served as a basis for this purpose. The main results of this collaboration were summarized in [2]-[8] and briefly in *Chapter 3*.

The main aim of the dissertation was to work out a software module enabling resolving energy and economic effectiveness problems connected with applying a high-capacity heat pump intended for intensifying the geothermal energy utilization. There are some results available in this field in work [17]. Though it presents a mathematical model convenient solely for analyzing the effect of number of stages on heat pump energy efficiency. Economic viewpoint is out of consideration. Moreover, the author assumes use of refrigerants such as R11, R12 and R22 having negative impact on the environment. Further, since the author uses the enthalpy method, qualitative losses arising in each of the sub-regime are not taken into account. More useful information is available in works [11], [12], which contains thermodynamic relations necessary for mathematical model creation as well as the principle of energy systems decomposition. The model described in [17] does not enable us to express the isentropic efficiency of compression as a function of refrigerant volume flow rate at the compressor suction, which is crucial when considering high-capacity heat pumps applying turbocompressors.

The mathematical model is own-created. Its software representation was first realized in Turbo Pascal 6.0, and later on reworked by a professional programmer in Java, NetBeans 5.5.

2. Used methods, results

In order to fulfil the aims of the dissertation, the following partial tasks were accomplished:

1. Work out a general method for application of the principle of decomposition of heat pump system to partial heat pumps, which is the first decomposition level and elementary component types which is the second decomposition level.
2. Analyze the effect of the first and second decomposition level on energy conversion effectiveness applying the exergy method.
3. Work out a partial heat pump mathematical model as the base model according to mathematical description of elementary component types.
4. Work out a proper algorithm for heat pump steady operation model generation by means of base model as well as for energy efficiency and economic effectiveness analysis using the virtual model.
5. Transformation of algorithm to software module by means of convenient programming tools. Demonstration of applicability of the software for technical-economical analysis of integrating the heat pump into the structure of hybrid combined cycle plant under specific conditions of company Tepláreň Košice.

Realization output of this work is a simulation software MAMUHEP which is based on the use of heat pump steady operating regimes mathematical model as a function of ambient temperature. It was worked out on the basis of entropy-temperature method. This software can serve as a useful tool for solving several partial problems in the project preparation stage. It enables us to analyze energy and economic effectiveness of a selected heat pump variant under various conditions. Moreover, it may form the basis of a complex software pack applicable to solving problems connected with the whole combined cycle power plant structure. Exact details may may be modified within the scope of the project.

When working out the mathematical model, composition/decomposition principle was applied. According to *Chapter 5,* this means that the complex heat pump system is decomposed into partial heat pumps which constitute heat pump stages (first stage of decomposition). These partial heat pumps are then decomposed into four sub-regions with analogous mathematical description (second stage of decomposition). According to *Chapter 7,* mathematical model of partial heat pump is created on the basis of mathematical description of its sub-regions (first stage of composition), in which entropy-temperature theory is applied. Mathematical model of the heat pump is fictive and is generated by the simulation software MAMUHEP, which applies this general model to each of the partial heat pumps, as it is described in *Chapter 8 - 10* (second stage of composition). Its main result is the power balance of heat pump steady operating regime as a function of ambient temperature which serves as the basis of economic effectiveness and energy efficiency analysis.

In spite of the fact that the work has been inspired by the idea of hybrid combined cycle power plant with combined heat and power production that could replace the outdated technology of the DHN in

Košice (see *Chapter 2*), the simulation software module is drawn up generally and therefore can be used in similar applications. Moreover, through use of thermodynamic relations by cybernetic methods it contributes to general theory and practice of energy effeciency and economic effectiveness analysis of high-capacity heat pumps. The aims of this dissertation according to *Chapter 2* may be considered as fulfilled.

3. New scientific results, theses

The following theses can be stated based on the collaboration with the Technical University in Košice:

Thesis 1 (3.2. subsection, [2]-[8])

Feeding the geothermal energy into the steam cycle by means of feed water preheating is more advantageous than its use for merely heating purposes. This is caused by the fact that the condensate temperature at the condenser outlet is 20-30 K lower than the primary geothermal energy carrier returning from the District Heating Network., and thus its enthalpy can be utilized to a higher extent. Additionally, use of geothermal energy in cogeneration (similarly to that of natural gas) represents a higher qualitative level.

Thesis 2.1 (3.4. subsection, [46])

Effectiveness of a heating system may be expressed as a function of fuel consumption by *specific heating effect*. In the case of reversible heating system, which is say an ideal heat pump, fuel amount necessary for generating exergy flow of heating capacity is necessary, hence exergy efficiency is $\varphi = 1$. Anergy flow is gained from the surroundings. Maximum, but in practice unreachable value of specific heating effect of natural gas utilizing systems changes in the range ξ_{rev} = 8.71÷60.94 for ambient temperature range $t = <-15; 15>$ °C.

Based on the specific heating effect value, the following groups of real heating systems can be created:

- conventional heating systems, for which $\xi \leq 1$,
- systems utilizing cogenerated heat, for which $\xi \geq 1$, but its exact value cannot be determined by means of the laws of thermodynamics,
- heating systems based on heat pump utilization, for which $\xi \geq 1$, but unlike in the case of systems utilizing cogenerated heat, its exact value can be determined, and the system utilizes reversed thermodynamic cycle.

Thesis 2.2. (3.4. subsection, [46])

Exergy efficiency of conventional heating systems is very low. Its value is $\varphi < 0.016$ for 15 °C ambient temperature and $\varphi < 0.115$ for –15 °C ambient temperature, and its year-round average is approximately φ = 0.05. Comparing this value to the efficiency of a combined cycle power plant, which is approximately 0.6, it is evident, that **use of natural gas in conventional heating systems is a „thermodynamic barbarism".** This fact is a result of the validity of 2. law of thermodynamics. Gas boiler manufacturers are not able to improve it significantly even if they manufacture ideal boilers with no losses, since the high quantitative efficiency could not counterbalance the very poor qualitative efficiency.

Thesis 2.3. (3.4. subsection)

Replacement of conventional heating systems by those applying heat pump is undoubtedly an advantageous solution from both the environmental and energy efficiency point of view. However, competitiveness of unconventional heating systems applying heat pump in comparison with those utilizing cogenerated heat is questionable. This dilemma is quite rare, since heat pumps are usually applied for decentralized heat supply, while cogenerated heat is used for centralized heat supply.

The combination of cogenerated heat and heat produced by means of a heat pump is generally questioned. This is justified in the case if the heating capacity of the heat pump can be effectively replaced by heat produced in cogeneration. Additional investment costs can then be saved. However, this statment cannot be considered as general, since the described solution is effectively realized in several cases. The disctrict heating system operating in Malmö, Sweden represents such a solution.

The software-module worked out within the scope of dissertation will enable us to decide, if use of geothermal resources of Košice basin should be realized by integrating it into the scheme of proposed hybrid combined cycle power plant or independently from it. Furthermore, it serves as a convenient tool for resolving several problems connected with the heat pump design.

The following theses connected with the high-capacity heat pump can be stated based on my own work:

Thesis 3 (5.1. subsection)

From the analysis carried out on dividing the heat pump into partial heat pumps and sub-regions follows, that use of non-symmetric variant is not justified in spite of the fact, that it seems meaningful in our specific case, when change in the heating water temperature in the condenser is is approximately half of that of the secondary geothermal energy carrier in the evaporator. Applying two symmetric heat pumps instead of a single non-symmetric is meaningful from the point of view of energy efficiency. When assuming the use of two lower-capacity condensers, it is more probable that mass-produced components can be applied, thus investment costs could be lower.

Thesis 3.1 (6.4. subsection, [1])

Except of the exergy efficiency defined in [19] another indicator can be defined for when comparing heat pump variants. Specific irreversibility rate can be defined as a ratio of total exergy loss and exergy of the heating capacity:

$$\alpha = \frac{\dot{I}}{\dot{E}^{Q_H}}.$$

Specific irreversibility rate is $\alpha < 1$ in case of more efficient solutions (two or more stages, high compression efficiency), while it is $\alpha > 1$ in case of less efficient solutions.

Thesis 3.2 (6.5. subsection, [1], [36])

Although total irreversibility rate decreases with the number of stages, its influence is negligible if number of stages is higher than 3. On the other hand, constant costs (service, maintenance) increase with the number of stages. Therefore, three-stage variant might be a technical-economical optimum. The validity of this statement can be analyzed by means of the software-module.

Thesis 3.3 (6.5. subsection)

In high-capacity heat pumps using turbocompressors, compression takes place with high efficiency. Consequently, relative irreversibility rate of the throttling devices is the highest. Contrarily, in low-capacity heat pumps using scroll or piston compressors compression efficiency is significantly lower, and therefore relative irreversibility rate of compressors is dominant, in spite of the fact that throttling is a purely dissipative process.

Thesis 4 (8.3. subsection)

According to [19] and based on own considerations the following equations will be used when calculating refrigerant parameters depending on its state:

1. Saturation pressure as a function of temperature

$$p = K_1 + K_2.t + K_3.t^2 + K_4.t^3 + K_5.t^4$$

2. Saturated liquid specific enthalpy as a function of temperature

$$h = K_6 + K_7.t + K_8.t^2 + K_9.t^3$$

3. Saturated vapor specific enthalpy as a function of temperature

$$h = K_{10} + K_{11}.t + K_{12}.t^2 + K_{13}.t^3 + K_{14}.t^4 + K_{15}.t^5 + K_{16}.t^6$$

4. Saturated liquid specific entropy as a function of temperature

$$s = K_{17} + K_{18}.t + K_{19}.t^2 + K_{20}.t^3$$

5. Saturated vapor specific entropy as a function of temperature

$$s = K_{21} + K_{22}.t + K_{23}.t^2 + K_{24}.t^3 + K_{25}.t^4 + K_{26}.t^5 + K_{27}.t^6$$

6. Saturation temperature as a function of pressure

$$t = K_{28} + K_{29}.p + K_{30}.p^{\frac{1}{2}} + K_{31}.p^{\frac{1}{3}} + K_{32}.p^{\frac{1}{4}}$$

7. Superheated vapor specific enthalpy as a function of temperature and pressure

$$h = K_{33}.p + K_{34}.p^2 + K_{35}.T + K_{36}.T^2 + K_{37}.p.T + K_{38}$$

8. Superheated vapor specific entropy as a function of temperature and pressure

$$s = K_{39}.p + K_{40}.p^2 + K_{41}.T + K_{42}.T^2 + K_{43}.p.T + K_{44}$$

9. Superheated vapor temperature as a function of pressure and specific enthalpy

$$t = K_{45}.\ln p + K_{46}.(\ln p)^2 + K_{47}.h + K_{48}.h^2 + K_{49}.\ln p.h + K_{50}$$

10. Superheated vapor specific enthalpy as a function of pressure and specific entropy

$$h = K_{51}.\ln p + K_{52}.(\ln p)^2 + K_{53}.s + K_{54}.s^2 + K_{55}.\ln p.s + K_{56}$$

11. Saturated liquid density as a function of temperature

$$\rho = K_{57} + K_{58}.t + K_{59}.t^2 + K_{60}.t^3 + K_{61}.t^4$$

12. Saturated vapor density as a function of temperature

$$\rho = K_{62} + K_{63}.t + K_{64}.t^2 + K_{65}.t^3 + K_{66}.t^4 + K_{67}.t^5 + K_{68}.t^6$$

13. Superheated vapor density as a function of pressure and temperature

$$\rho = K_{69}p + K_{70}.p^2 + K_{71}.T^{-1} + K_{72}.T^{-2} + K_{73}.p.T^{-1} + K_{74}.p^2.T^{-1} + K_{75}$$

Unlike in [19], polynomial expression is recommended in equation 3., 5. and 12.. If pressure is given in kPa and temperature in °C, then specific enthalpy is obtained in kJ/kg and specific entropy is obtained in kJ/(kg.K). Equations for calculating the superheated vapor parameters form an exeption. In these temperature is given in K. Specific enthalpy and entropy of subcooled liquid is calculated as of that of saturated liquid of corresponding temperature.

In [19] the corresponding coefficients used in equations 1.-13. were only derived for single refrigerant (R134a) that is applicable in high-capacity heat pumps. However, applicability of these coefficients is limited, especially in the superheated vapor state. For this reason coefficient values had been derived by means of regression for each refrigerant identified as applicable in high-capacity heat pumps. Coefficient values are listed on page 72-73 of the dissertation. The coefficients are valid in the case of refrigerants R134a, R290, R1270 and Fluid H in the saturated temperature range 10-80 °C, those derived for R245fa and R600a are valid in the saturation temperature range 10-95 °C and 1-45 K superheat, which is fairly sufficient from the point of view of mathematical model. The reference state is the one created by the IIR – IIF (International Institute of Refrigeration), which is saturated liquid specific enthalpy for 0 °C temperature is 200 kJ/kg, and its specific entropy is 1 kJ/(kg.K).

Although superheated vapor specific entropy can be according to eq. 8 calculated with low relative inaccuracy, the absolute inaccuracy is not acceptable. However, specific enthalpy can be accurately calculated as a function of specific entropy and pressure according to eq. 10, specific entropy can then be calculated by means of iteration very accurately.

Thesis 5 (8.4. subsection)

When assuming the use of pentafluoropropane or isobutane as a refrigerant in high-capacity heat pumps, it is necessary to superheat the refrigerant before suction by the turbocompressor. Otherwise, compression would partially take place in the two-phase region. This would lead to erosion, which has a negative impact on the lifetime. Suction Line Heat Exchanger can be effectively applied when ensuring the necessary refrigerant superheat. It is a low-cost step that does not negatively impact COP with the assumed refrigerants. In the Suction Line Heat Exchanger, refrigerant either in the state of saturated liquid or subcooled liquid at the condenser outlet or in the state of subcooled liquid at the subcooler outlet exchanges heat with the refrigerant in the state of saturated vapor at the evaporator outlet. The necessary superheat increases with the compression efficiency. Such an algorithm had been built into the software-module, that enables us to calculate the minimum superheat within the assumed conditions.

Thesis 6 (Chapter 11)

The results of a test run show that if the temperature of both the heating water and secondary geothermal energy carrier at the heat pump inlet decreases linearly with the ambient temperature, and compression isentropic efficiency changes with the refrigerant volume flow rate, heat pump COP can have a local maximum. The ambient temperature corresponding to maximum COP primarily depends upon:

- the compression efficiency-refrigerant volume flow rate function in each stage,
- the evaporating and condensing temperature distribution as a function of ambient temperature.

4. Applicability of results

Realization output of this work is the simulation software MAMUHEP which is intended for modeling steady state regimes of a high capacity heat pump as a function of ambient temperature. This software can serve as a useful tool for resolving several problems connected with the preparation stage of the project. It enables the user to analyze the energy efficiency and economic effectiveness of a selected heat pump variant under various conditions. Moreover, it can form the basis of a complex software pack applicable to resolving problems connected with the whole combined cycle power plant. Exact details may be modified within the scope of the project.

In spite of the fact that the work has been inspired by the idea of hybrid combined cycle power plant with combined heat and power production that could replace the outdated technology of the DHN in Košice, the simulation software module is drawn up generally and can therefore be used in similar applications.

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7. Research works

[48], [49], [50], [51], [52]

In 2006-2007 main author of two research studies, co-author of three research studies, each of them published internally at Ingersoll Rand Climate Control Technologies, R&D Center Prague. More detailed information about the studies are confidential.

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9. Symbols

ξ	-	specific heating effect
φ	-	exergy efficiency of the heating system
t	°C	temperature
T	K	thermodynamic temperature
h	J/kg	specific enthalpy
s	J/(kg.K)	specific entropy
ρ	kg/m^3	density
p	Pa	pressure
$\dot{E}^{Q}$	W	heat-flow exergy
$\dot{I}$	W	irreversibility rate
α	-	specific irreversibility rate