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REDUCTION OF ENERGY CONSUMPTION OF ABSORPTION HEAT PUMPS

Booklet of PhD dissertation

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1. RESEARCH ASSIGNMENT

1.1. INTRODUCTION

Climate change is the biggest challenge of our time, the impact of which has serious consequences for both nature and humanity. We, engineers, must also give an effective answer to this. We must control to increase of the energy consumption - especially with regard to the increase in the environmental impact of the energy consumption. One of the tools of this endeavor is the absorption heat pump, where the majority of the energy source is heat, which can be waste heat from other technological processes or even solar energy.

1.2. OBJECTIVES

This dissertation has three main sections. The first step is to select the system that will be developed, then I will examine it, on the basis of which the goal to be achieved is formulated. The next two sections contain the two solution options given for this.

1.2.1. SELECTION OF THE SYSTEM TO BE EXAMINED

The field of absorption heat pumps is quite large, and our possibilities are limited. The research had to be narrowed down to the most developable equipment and one of the most versatile pairs of working fluid. This became the absorption heat pump with solution pump and the ammonia-water refrigerant pair.

1.2.2. CREATING A MATHEMATICAL MODELL OF THE SYSTEM

The next step was the mathematical description of this heat pump, because its behaviour - the response to changes in input parameters, shows the possibility of reducing energy consumption.

1.2.3. MODELING OF THE PHYSICAL MODELL OF WORKING FLUID PAIR

For the mathematical modelling of the heat pump system, it was necessary to generate functions describing the physical properties of the ammonia-water medium pair. Using these, the entire absorption system could be described.

1.2.4. SYSTEM ANALYSIS, AND THE POSSIBLE WAY OF DEVELOPMENT

The behaviour of the model can be used to find and identify opportunities to reduction of energy consumption. The results show that the best result can be achieved by reducing the energy demand of the solution pump or replacing that entire unit, because it uses not thermal energy but electrical energy. This has been the focus of further research.

1.2.5. SOLUTION PUMP DRIVEN BY HOT AIR ENGINE

It is obvious that the solution pump obtains the energy required for its operation from the available heat. For this purpose, a new type of heat-air engine was developed, which is significantly simpler than the existing versions, but nevertheless somewhat more efficient than those, which is able to utilize the heat source of the heat pump. The process of its design, its examination, evaluation and technical description of this became part of the dissertation. During the analysis of the system, I revealed their weaknesses. This set myself the goal of developing another, more favorable construction.

1.2.6. PUMP WITH STEAM WORKING MEDIUM

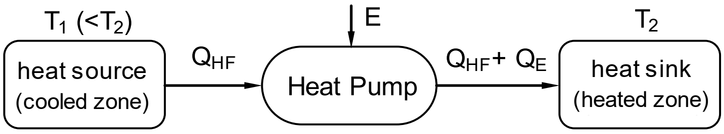
My goal was to create a machine with the same operating principle as a hot air engine, whose working medium is steam. Due to the steam working medium, the power density is much higher. This engine was built in a free-piston version. It has a simple structure, but it is already self-starting, i.e. it starts without an external energy source, so it can be used directly as a pump. The process of design, testing, evaluation, and technical description of this machine were also part of the dissertation. Finally, I write a few words about the further areas about use of this new engine.

2. SCIENTIFIC PRELIMINARIES

2.1. ABSORPTION HEAT PUMPS

2.1.1. WHAT IS A HEAT PUMP?

A heat pump is a machine that we use to extract the heat from area with lower temperature and transport it to the area with higher temperature. (Fig. 1). For all of this, of course, we need to invest some energy [1].



$$COP = \frac{Q_{useful}}{E_{invested}}$$

Figure 1: *Scheme of the heat pump [1].*

The equipment can be used for both cooling and heating. In the first case, the low-temperature cooled zone is important for us, and the environment is the heat sink. In the second case, the heated zone is important, and the heat source is mostly the environment. The main character of the heat pump is the coefficient of performance (its abbreviation is COP). This is the amount of heat absorbed or delivered, projected onto the amount of energy invested. This is not a classic efficiency. It can be greater than 1.

2.1.2. ABSORPTION HEAT PUMP WITH SOLUTION PUMP

There are two completely different types of absorption heat pumps: the constant-pressure and the variable-pressure system, also called solution-pumped system, invented by Ferdinand Carré in 1859 [2, 3]. This dissertation deals only with this second type because of its potential for improvement.

2.1.3. DESCRIPTION OF OPERATION

The apparatus (Fig. 2) contains a working fluid pair, in our case ammonia-water solution (typically containing 30-40% refrigerant). This is heated in the generator to 80-120 °C. The ammonia is evaporates as hot steam and enters the aftercooler. It cools back to 50-70 °C, refines the refrigerant, then in the condenser cools to 30-40 °C and liquefies, then passes through the expansion valve, enters the low pressure zone and evaporates, thus removing heat at low temperatures. It then enters the absorber at 30-40 °C where it goes back into solution. The thermodynamic cycle is shown in Figure 3. The process makes solution of the generator weaker and the solution of absorber richer, so a pump is needed to circulate the solution. Also a heat exchanger is required, because the temperature difference between the two fluid streams is very high [4].

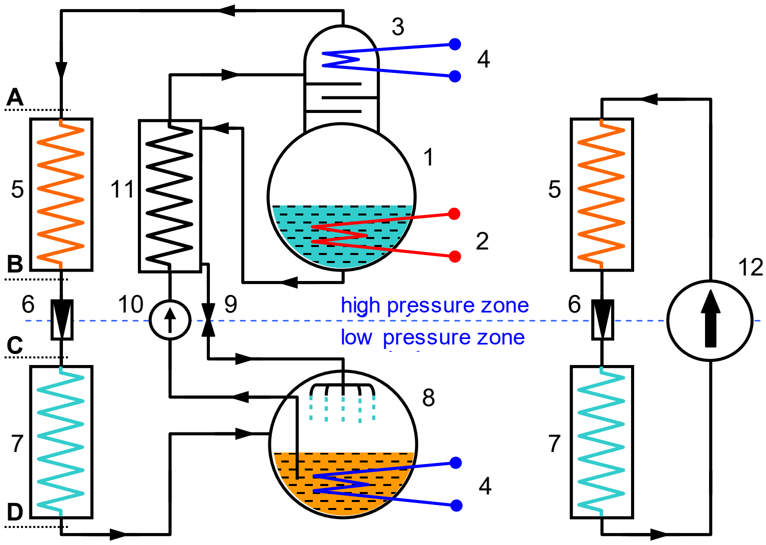


Figure 2: *Absorption heat pump (left) and a compressor heat pump (right)*

1. generator, 2. heating, 3. after cooler, 4. cooling 5. condenser, 6. choke, 7. evaporator, 8. absorber, 9. control valve, 10. solution pump, 11. heat exchanger. 12. compressor [5].

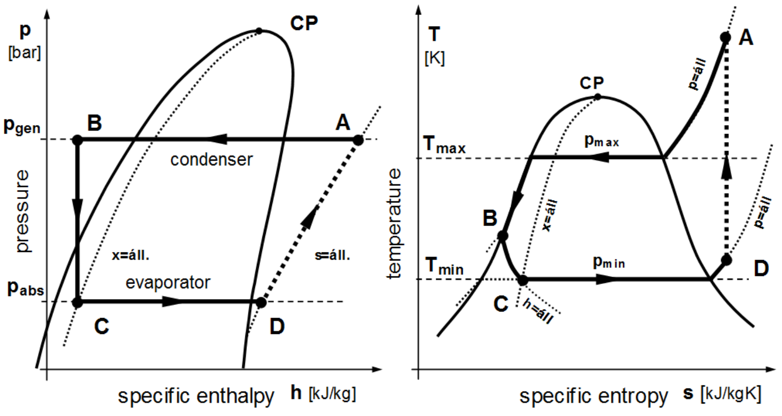
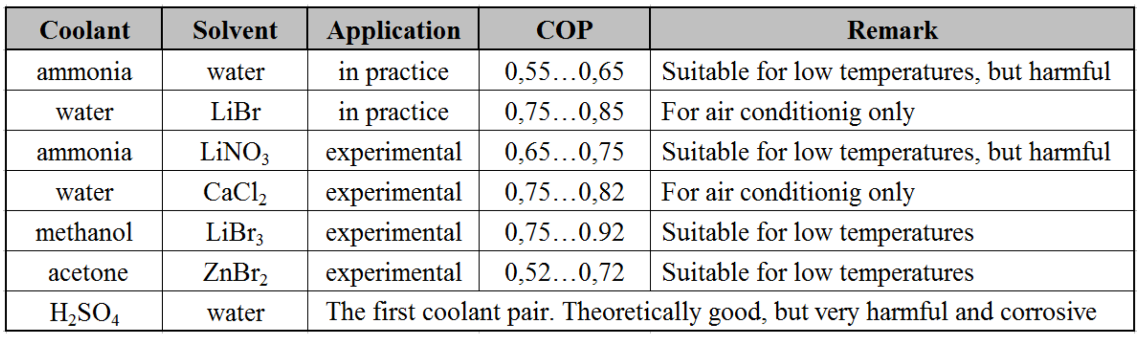


Figure 3: *Pressure-enthalpy (left) and temperature-entropy diagram (right) of the process. The points A, B, C, D correspond to the points marked in figure 2.*

2.1.4. COEFFICIENT OF PERFORMANCE

The cooling circuit can also be created with other media pairs (Table 1). The two main conditions for this are unlimited solubility and a significant difference in the boiling point. The table contains the COP, which is of course a design or guideline value, as it also depends significantly on the operating conditions. These COP values are far below the nominal values of compressor heat pumps, but they use electrical energy, and the absorption processes mostly use heat.



Coolant	Solvent	Application	COP	Remark
ammonia	water	in practice	0,55…0,65	Suitable for low temperatures, but harmful
water	LiBr	in practice	0,75…0,85	For air conditionig only
ammonia	$LiNO_3$	experimental	0,65…0,75	Suitable for low temperatures, but harmful
water	$CaCl_2$	experimental	0,75…0,82	For air conditionig only
methanol	$LiBr_3$	experimental	0,75…0.92	Suitable for low temperatures
acetone	$ZnBr_2$	experimental	0,52…0,72	Suitable for low temperatures
H_2SO_4	water	The first coolant pair. Theoretically good, but very harmful and corrosive		

Table 1: *Applicable working fluid pairs [6].*

2.2. HEAT DRIVEN PISTON ENGINES

2.2.1. TYPES OF HEAT DRIVEN ENGINES

There are three families of reciprocating heat engines [7]. The family of steam engines [8], the other is the family of internal combustion engines, and the third is the family of hot air engines. This is quite unknown, even though their history is over two hundred years old. Robert Stirling [9] built the first in 1816. This machine family is important to us because it can utilize the low-temperature heat source of absorption cooling.

2.2.2. WORKING PRINCIPLE OF THE HOT AIR ENGINES

There are several versions of the Stirling engine, but the mode of operation is the same. Its condition is the temperature difference. The thermodynamic circuit named after the inventor is shown in figure 4/a. The idealized Stirling cycle consists of four sections: isothermal compression (1-2), isochoric heating (2-3), isothermal expansion (3-4), and finally isochoric cooling (4-1). This process approximates the Carnot cycle (Fig. 4/b), which consists of the following four sections: isothermal compression (1-2), isentropic compression (2-3), isothermal expansion (3-4), then isentropic expansion.

2.2.3. BASIC TYPES OF HOT AIR ENGINES

According to their arrangement, there are three basic types, these are the α, β and γ variants [10]. There are two crank rods on their main shaft, which are mounted in 90° angle. When the machine compresses, the bulk of the working medium is on the cold side, then it is transferred to the warm side, and the expansion begins. These machines are mostly slow-moving (100 – 1000 1/s), because the heat exchange takes time [11, 12]. The thermodynamic process can be considered quasi-static, so the volume changes at constant temperature. Figure 5 shows the basic models [13].

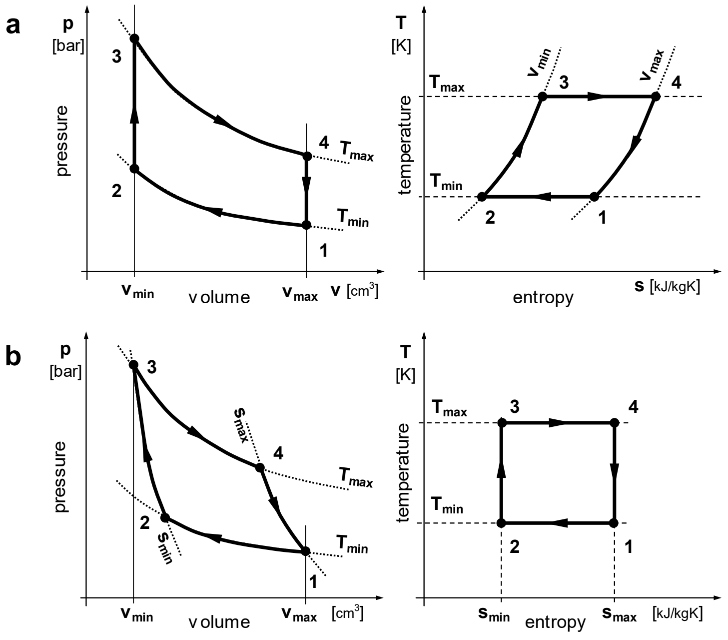


Fig. 4: *Pressure-volume and temperature-entropy diagrams of Stirling cycle (a), and Carnot cycle (b).*

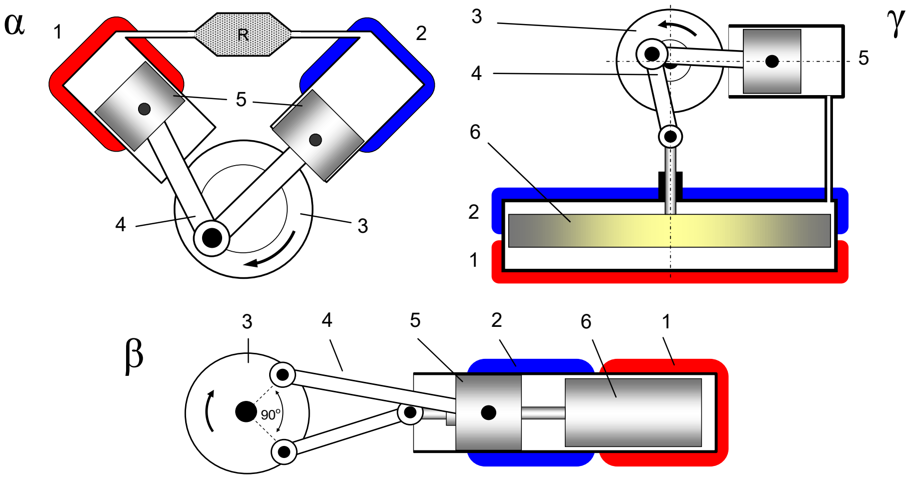


Fig. 5: *The construction of α, β and γ type machines: 1. heating, 2. cooling, 3. flywheel, 4. connecting rod, 5. piston, 6. transfer piston, R: regenerator.*

There are also other versions, such as the Ringbom machine [14] where the pressure controls the transfer piston, and the so-called rotary hot air machine [15] where the transfer of the gas is ensured by a special crankshaft rotating in a closed space. But they also work according to the Stirling cycle. In my dissertation, I described a hot air engine that differs from all of these.

3. EXAMINATION OF ABSORPTION HEAT PUMP

The most useful way to determine how to increase efficiency is to build a mathematical model to determine the effect of the given input parameters on the COP value. The model requires functions with two variables describing the physical parameters of the ammonia-water pair. These variables are temperature and concentration, and pressure and concentration. Thus, the first step is to generate these three-dimensional curves.

3.1. PHYSICAL PROPERTIES OF THE AMMONIA-WATER COOLANT

I used the work of Carl G. Almén [16] as a starting point for the investigation of the physical properties, although there are several similar studies [17, 18, 19], which I tried to develop further. The aim is to produce simple approximations of the physical properties of the coolant with low error [20]. The two most important material properties are shown in Figures 6, 7 and 8.

3.1.1. VAPOR PRESSURE CURVE

The vapour pressure curve shows the saturated vapour pressure in case of given concentration of solution at a given temperature: (Fig 6. and 8.)

$$p(t,x) = e^{A(x) - \frac{B(x)}{t + C(x)}} \tag{1}$$

Where: A(x), B(x), C(x):

$$A(x) = 11{,}675 \cdot \left(1 - 0{,}223x^{0{,}5} - 1{,}55x^{1{,}5}\right) \tag{2}$$

$$B(x) = 3840 \cdot \left(0{,}126x^{2{,}62} - 0{,}1157x^{1{,}62} - 0{,}62x^{0{,}62} + 1\right) \tag{3}$$

$$C(x) = (229 + 47{,}7x - 20x^{2}) - 7\sin(2{,}8x) - 1{,}5\sin(8{,}5x) \tag{4}$$

3.1.2. EQUILIBRIUM CURVE

The equilibrium curve shows the ammonia concentration in the vapor above the solution with a given concentration at a given pressure: (Fig 7. and 8.)

$$y(p,x) = B_y(x) - e^{A_y(p) \cdot x} \tag{5}$$

Where $A_y(p)$, és $B_y(x)$:

$$A_y(p) = 1{,}5413 \cdot e^{-p} + 2{,}5151 \cdot \ln p - 14{,}2715 \tag{6}$$

$$B_y(x) = 1 - 0.0353 \cdot \sin(\pi \cdot e^{-8x}) \tag{7}$$

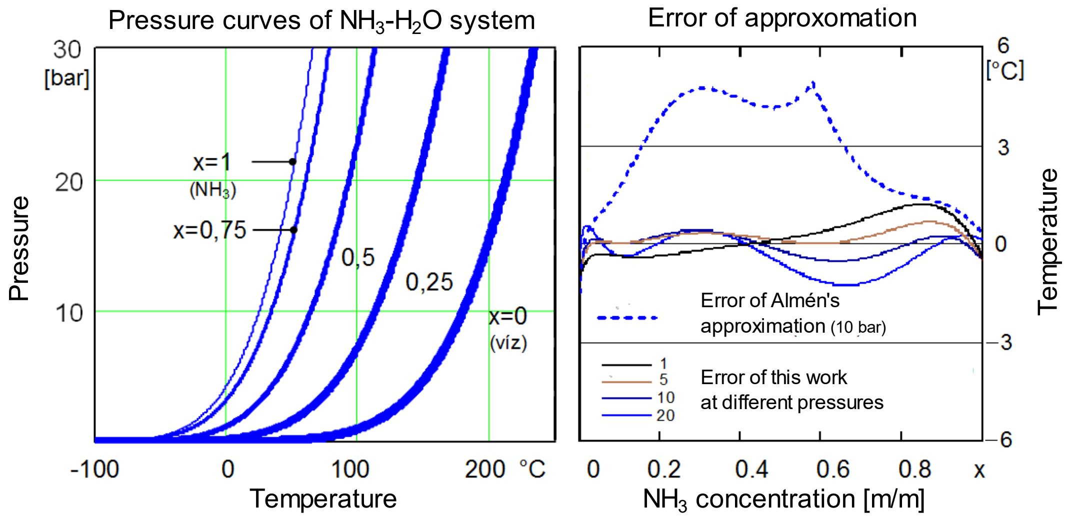


Fig 6: *Vapour pressure curves at different concentrations and the error of approximation.*

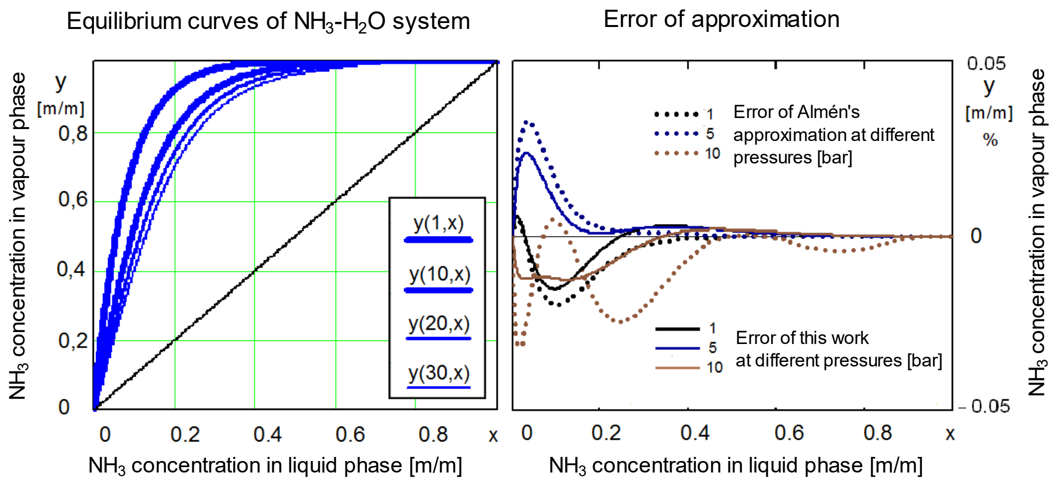


Fig 7: *NH_3-H_2O equilibrium curves at different pressures and the error of approximation.*

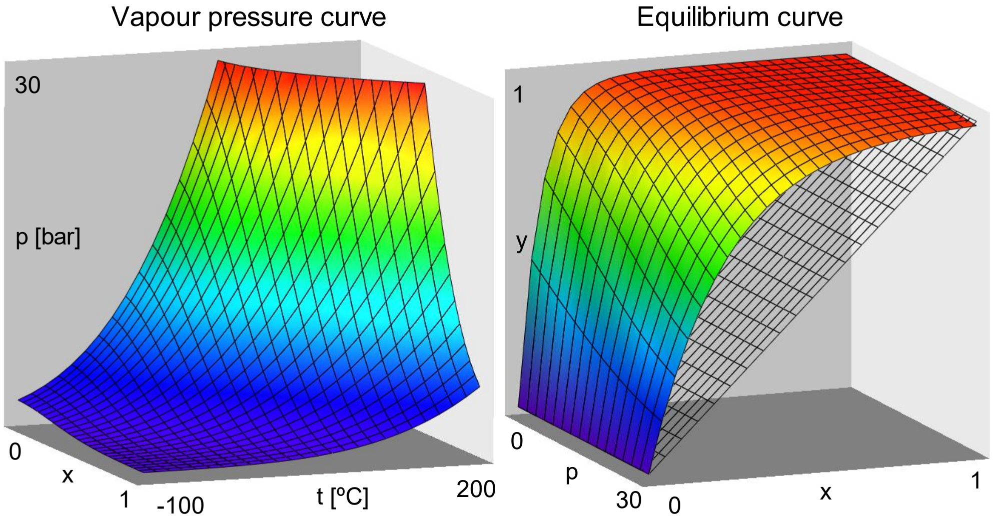


Fig 8: *3D representation of vapour pressure and equilibrium curve of NH_3-H_2O pair. Pressure: p [bar], temperature: t [ºC], NH_3 concentration in solution and vapour x and y [m/m].*

3.2. MODEL OF THE ENTIRE PROCESS AND ITS RESULTS

In addition to the above, the bubble and dew point curves, the specific heat and density of the unsaturated solution, the specific heat of the superheated vapour and the enthalpies of the solution and vapour are required. Using these, a model of the complete heat pump cycle can be constructed by suitably formulating the mass balance and energy balance equations. The results for the COP values are shown in Figure 9. The red line shows the values in base case and the blue line shows the values if the aftercooler cooled by solution from the absorber. The temperatures of the generator, aftercooler, condenser and absorber are 100°C, 60°C, 35°C, 30°C, The concentration of the generator and absorber are 37% and 44% (m/m%) - unless these are the input variables. Examining the results, I set out to improve the solution pump drive.

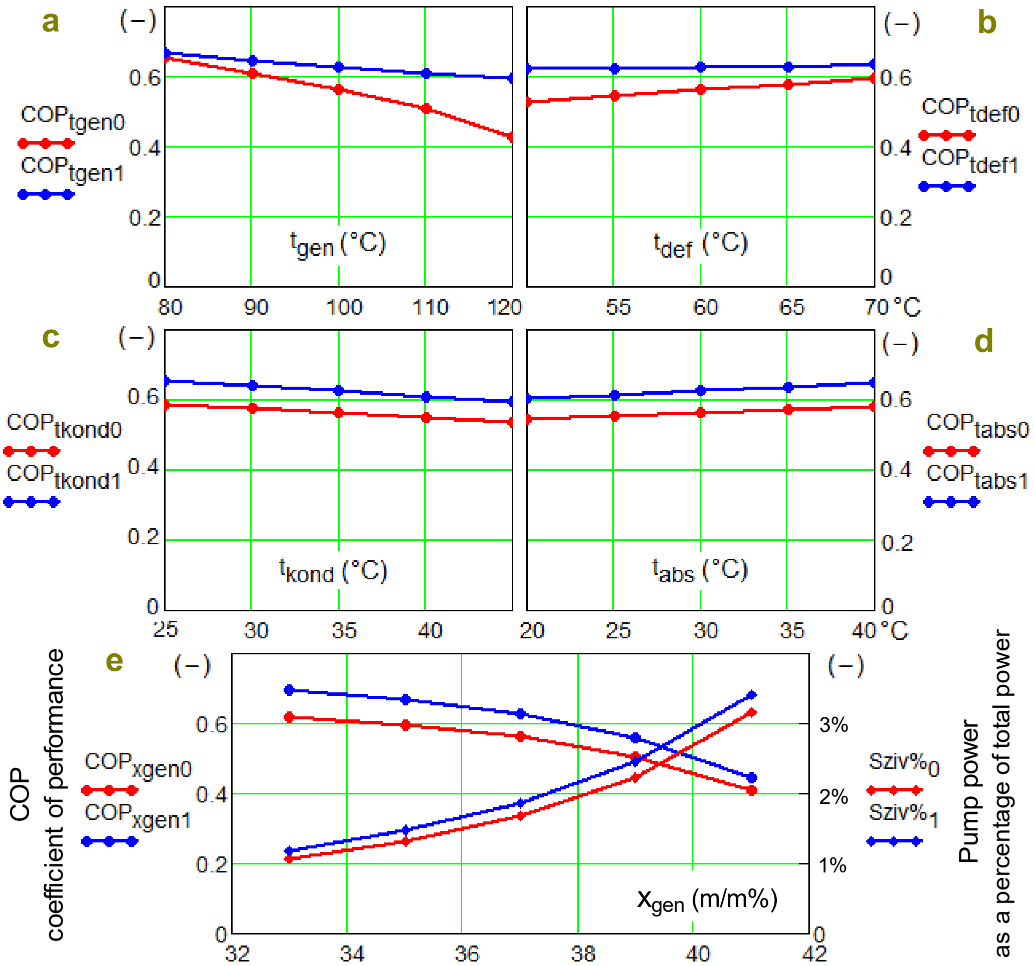


Fig 9: *The COP values compared temperature of the generator (a), aftercooler (b), condenser (c) absorber (d) and the concentration of solution in generator (e) and the pump power in relation to the total power as a function of the solution quality (e)*
Blue line: cooling the aftercooler with the cold solution from the absorber.

4. APPLICATION OF HOT AIR ENGINE

The choice of the heat engine for the given task is obvious, because this heat engine has a version that can operate with the low-temperature heat source used by the absorption heat pump. [21, 22].

4.1. OWN DEVELOPED ENGINE

The machine I made is much simpler than the previous ones. It has only a single crank and piston. Here, the working piston itself moves the replacer cylinder. The cylinder leads directly into the hot side of the heat exchanger chamber. Opposite it is the cold side. This heat exchange chamber has cylindrical design, but with a larger diameter and concentric with the working cylinder. This space is filled, with some gap, by the replacer cylinder (Figure 10). The so-called control rod is fixed to the centre of the working piston, which passes through the centre of the replacer cylinder. This rod slides in the replacer cylinder without resistance, but has an adjusting screw at its base and at its end, so those start to pull and push the replacer before the top and bottom dead center at a certain distance to the proper position.

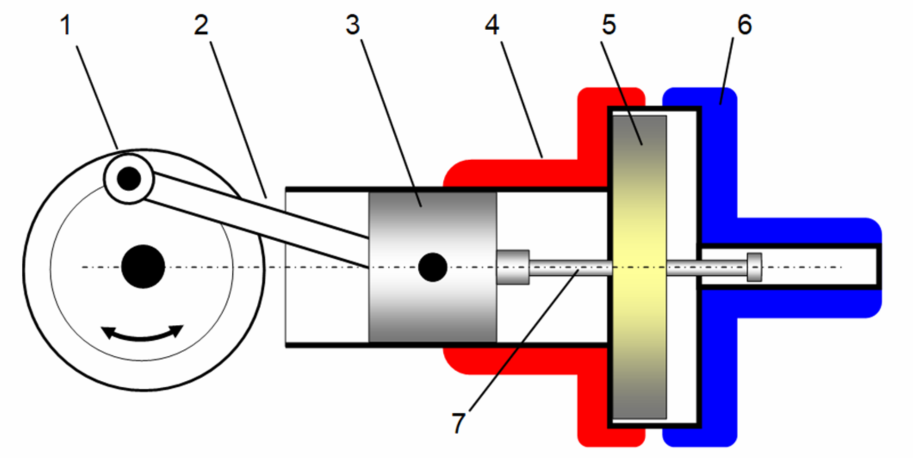


Fig 10: *Own developed engine: 1. flywheel, 2. connecting rod, 3. working piston, 4. heat exchanger, hot side, 5. replacer cylinder, 6. heat exchanger, cold side 7. control rod.*

4.1.1. DESCRIPTION OF WORKING PRINCIPLE

The first stroke is the compression phase (Figure 11/1). The piston starts from the bottom dead centre and compresses the gas by pushing it through the gaps of the replacer cylinder, which is still stationary. Thus a most part of the working fluid is on the cold side. Then, a certain distance before the top dead centre, the control rod reaches the replacer cylinder and starts to push it over to the cold side. It will then move with the piston for certain time, then, when it reaches the top dead centre, stays there, isolating the cold side of heat exchanger, giving room for the air on the hot side. (Figure 11/2) The air then heats up, its pressure increases so the second stroke, or can start.

In the expansion stroke, the increased pressure of the gas drives the piston backwards after it has reached the top dead centre (Figure 11/3). At this point, the replacer cylinder is still stationary and isolates the cold side of the heat exchanger chamber. However, a certain distance before the bottom dead center, the control rod pulls it back to its original position. It moves with the piston for a while, and when it reaches the bottom dead centre, it stays there, isolating the hot side of the heat exchanger chamber, giving way to air on the cold side. (Figure 11/4) Thus the next compression stroke can start.

An important difference compared to conventional engines is that here the direction of rotation of the crankshaft is arbitrary.

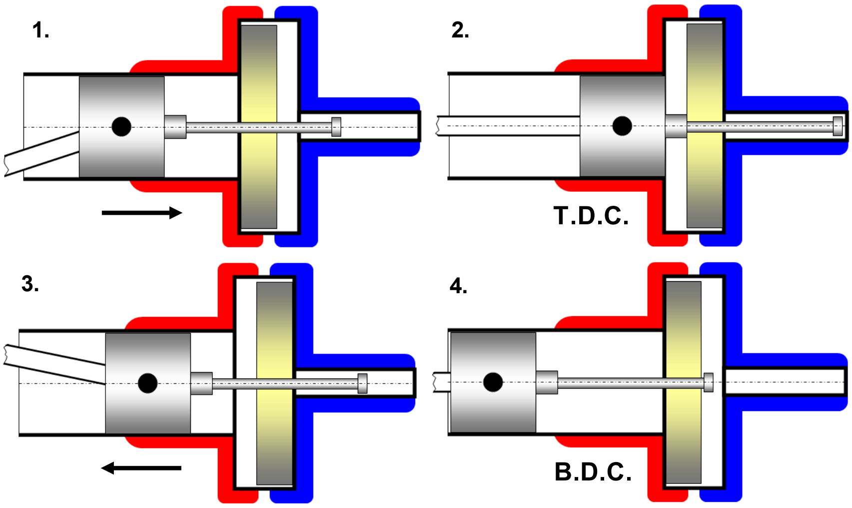


Fig 11: *Work phases of the own developed engine.*

1. compression, 2. top dead center, 3. expansion, 4. bottom dead center.

4.1.2. OPERATION OF THE ENGINE

First the motions of the piston and the replacer cylinder of the novel hot air engine must be described, because from this the volume changes can be calculated. Then the quasi-stationary pressure curve can be plotted and the indicator diagram can be constructed. This is illustrated in the left side of Figure 12, where the diagrams of a traditional machine with same parameters are shown as well. Finally, considered, that heat exchange takes time, at the right side of the Figure 12 are shown the calculated pressure curves and indicator diagram of the own developed hot air engine at different speeds.

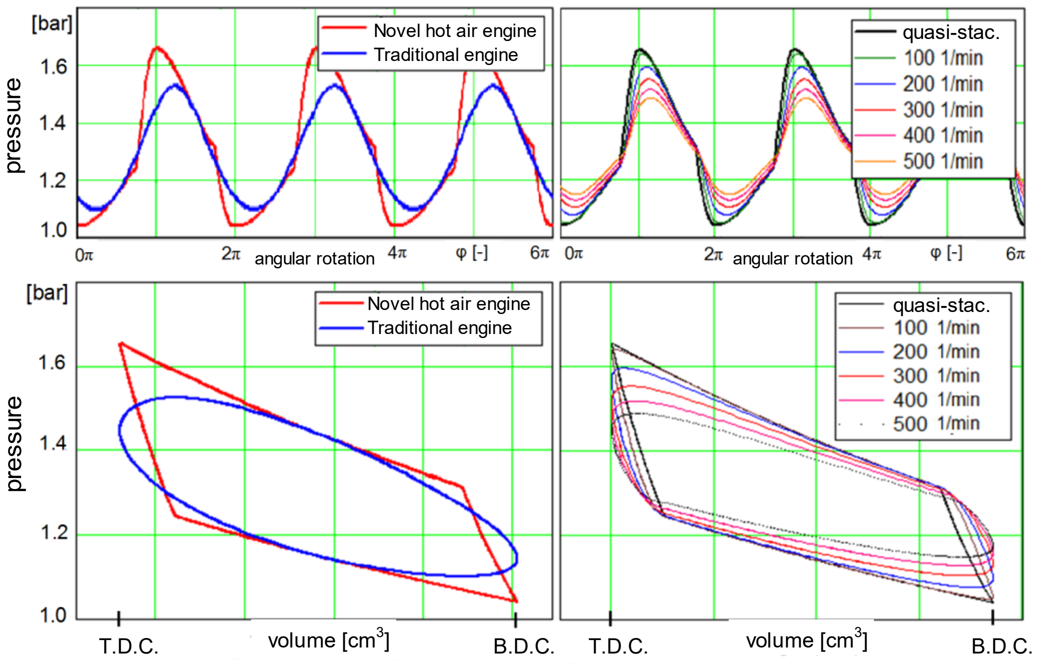


Fig 12: *The pressure curve (up) and the indicator diagram (down) of the engine, Quasi-stationary operation (left), operation at different speed (right).*

4.1.3. ENGINE PERFORMANCE CURVES

As a continuation of the thought process above, the internal characteristic curves of the motor can be written (Figure 13 left). These are the inner power and torque diagram. The motor, without load, makes 360 revolutions per minute. This means, that in this case, internal power can cover internal friction and flow losses. Subtracting these gives the shaft power and torque diagrams (Figure 13 right)

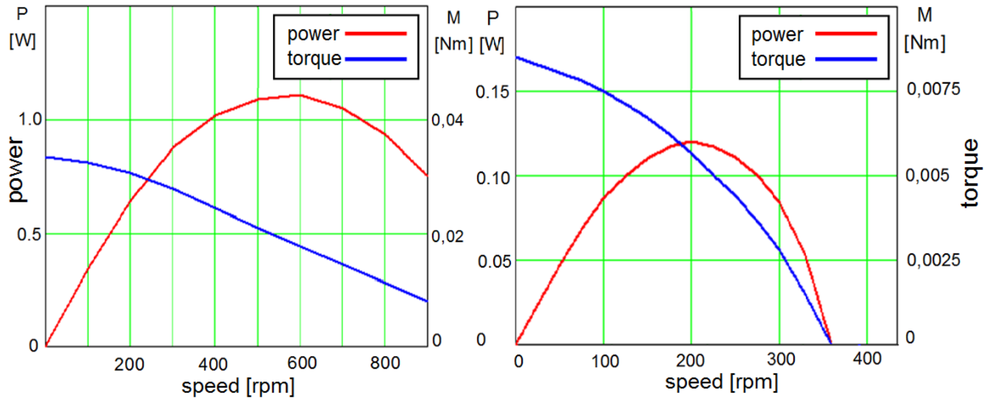


Fig. 13: *The internal (left) and external (right) characteristics of the novel engine.*

I built an experimental engine which works perfectly. So I could verify the calculations with measurements. The efficiency of the engine is good, but its power per volume is small. I therefore decided to develop another engine which works with steam.

5. APPLICATION OF STEAM PISTON ENGINE

The first and most important requirement for the machine is that it should run on the same energy source as the absorption system itself. So the machine should have a heat source with a temperature of 100-130 °C and a heat sink side of 30-50 °C. The second is that the equipment should be self-starting, i.e. not require any external energy to start. The third is that it should have a higher power output compared to its size, and simplicity is a further consideration.

5.1. OWN DEVELOPED ENGINE

The pump is actually a free-piston motor (Figure 14). Its main part is a tubular housing divided into two parts by a piston. The upper, sealed part is the working chamber, to which two non-return valves are connected, which determine the path of the pumped medium. This is a working part of the engine.

The driver part is under the working piston. This section of the cylinder below the working piston can be divided into two parts. Above is the heated section and below is the cooled section. In the space below the working piston is another piston, the displacer piston. But this is not fit the cylinder wall, there is a gap of about half a millimeter between them, i.e. a ring shaped gap around it. The function of this piston is not to seal, but to move the working fluid into the desired position. In the lower position, it forces it out of the lower, cooled part of the cylinder, which then rises and enters the thin ring gap between the cylinder wall and the heated part of the chamber, where the working fluid starts to boil (Figure 14 shows this situation). In the upper position, the level of the working fluid drops so much that the cooled wall of the machine becomes free, thus starting the condensation of the steam.

The control could be made as we saw with the hot air engine, but we don't need a crankshaft, flywheel or even a crank to perform this function. The two pistons, the working piston and the displacement piston, are connected by a spring, which compressed and stretched depending on the state of the machine, i.e. it stores energy. At the bottom of the machine, a magnetic ring is mounted under the replacer piston, which moves between two iron rings so acts as a motion limiter. So that stops the replacer piston in either the up or down position. The magnet releases when the spring tension reaches its attractive force. If so, the displacer piston changes its position.

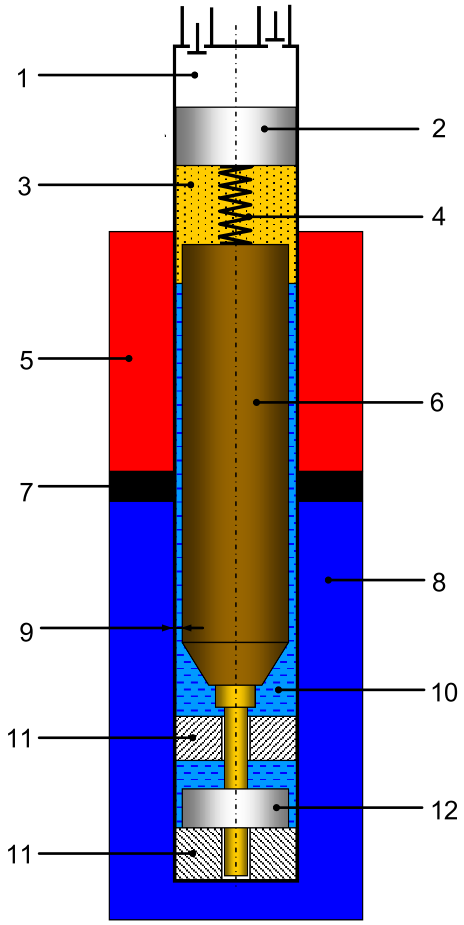


Fig 14: *The experimental machine:*

1. working space and the pumped medium, 2. working piston, 3. steam chamber, 4. connector spring, 5. heated section, 6. displacer piston, 7. insulation, 8. cooled section, 9. ring shaped gap, 10. working fluid, 11. iron ring, 12. magnet ring.

5.1.1. OPERATION OF THE ENGINE

This engine has also two-stroke, but its operation is divided into four phases. These four phases are shown in Figure 15, where magnetic positioning is not included for clarity.

In the first phase, both pistons are down, part of the medium is in the heated part of the space, so the pressure increases (Figure 15/1), this continues until the pressure of the steam space reaches the pressure of the pump part. The second phase then begins and continues until the working pump reaches the top dead centre (Figure 15/2). By this time, the spring has enough tension to cause the displacement piston to change position, the working fluid level to drop and make free the cold part of the heat exchanger, i.e. condensation of the working fluid begins. This is the third phase (Figure 15/3), which lasts until the vapour pressure drops to the suction pressure of the pump. In the fourth phase, the working piston starts to move downwards and when it reaches the bottom dead centre, the displacement piston changes position (Figure 15/4 shows the moment before the change) and the first phase can then start again.

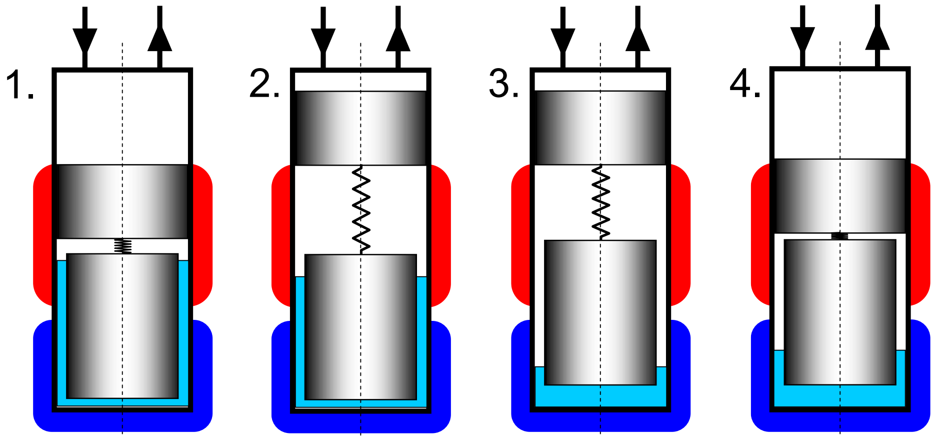


Fig 15: *The four phases of the operation of the engine.*

5.1.2. ILLUSTRATION OF THE WORK CYCLE

The work cycle of the machine is on the Figure 16. The four phases are indicated by Roman numerals. The left side of the figure shows the cycle on the pressure-enthalpy diagram. I and III represent isochoric processes, II and IV isobaric processes. The right side of the figure shows the time course of the physical properties.

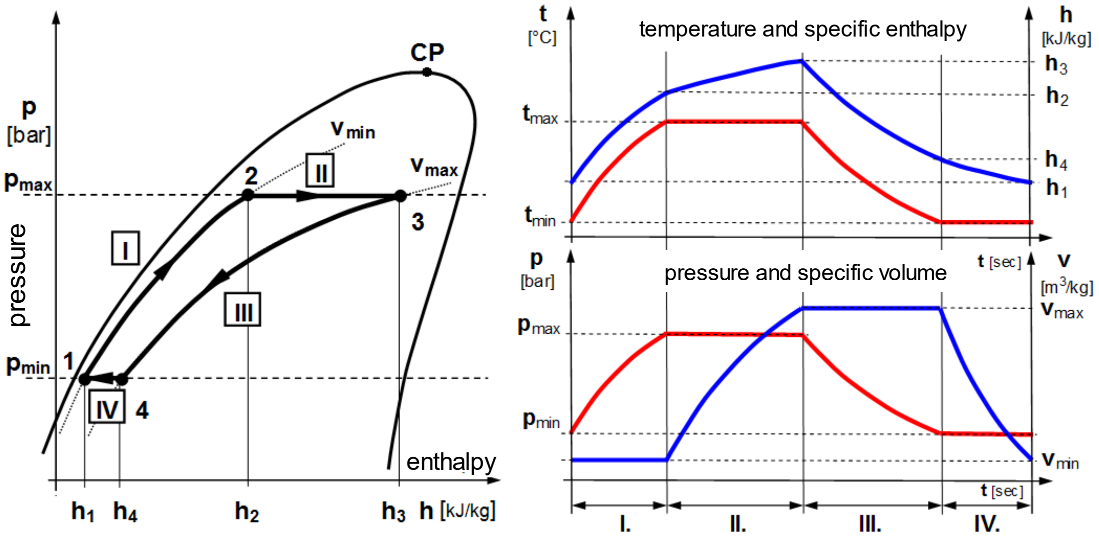


Fig 16: *Changes in physical properties during a work cycle.*

5.1.3. CALCULATION OF THE PHYSICAL PROPERTIES

The corner values of the cycle are easy to determine if the suction and discharge side pressures are known, but numerical calculations were needed to calculate them over time. The result of this, i.e. the changing of temperature, enthalpy, pressure and specific volume are shown in Figure 17, which shows one second of the work of our machine.

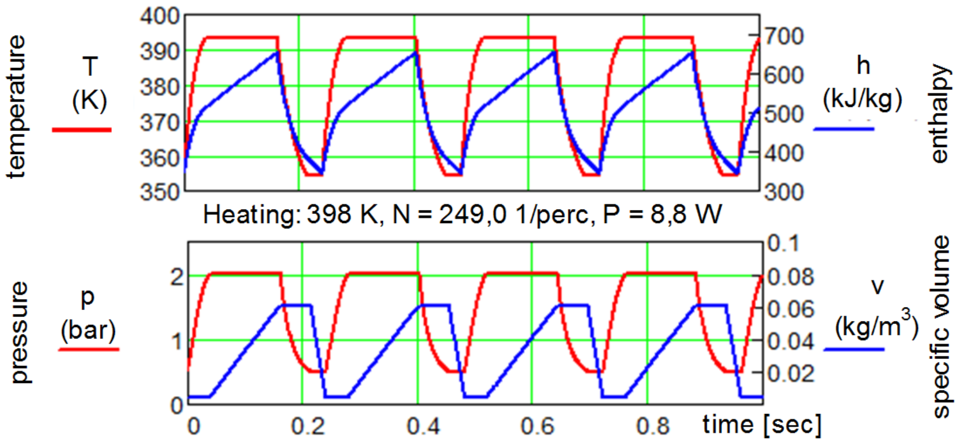


Fig 17: : *Changes in physical properties at 398 K heating temperature.*

The machine is now operating as a pump and the necessary calculations are made, so the pump characteristic curve can be plotted (Figure 18). This diagram shows the relationship between pressure and flow rate at different heating temperatures, where the cooling temperature is 80 °C in all cases.

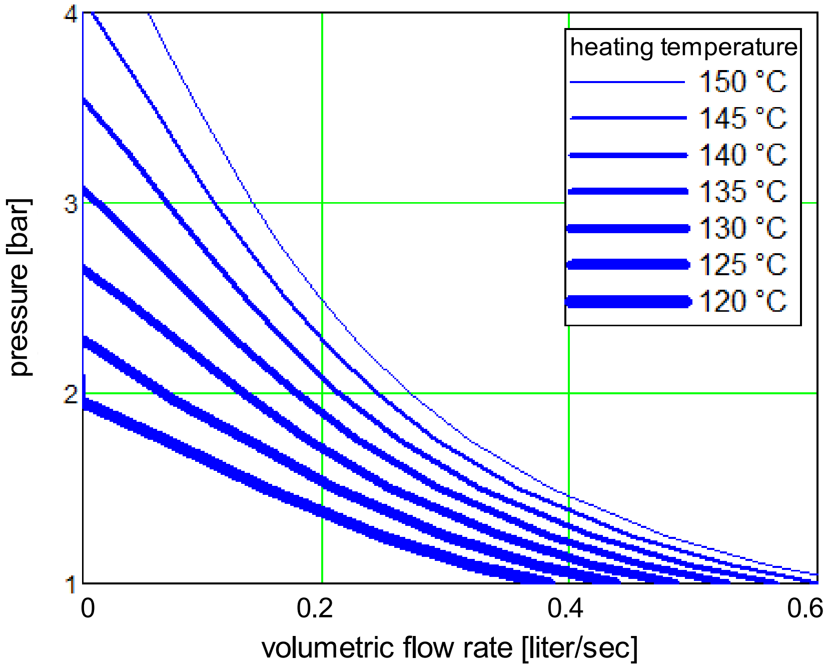


Fig 18: *Pump performance curves at different heating temperatures.*

Of course, in case of using a different working medium, we can choose other temperatures. In this case we would get similar curves, but with different values. So that machine can be adapted to various temperatures. However, an examination of this would exceed the size of this thesis.

6. THESES - NEW SCIENTIFIC RESULTS

1. I created a mathematical model of the working cycle of the ammonia-water absorption heat pump system that can be used efficiently in practice of engineering, in this context:
    a. I developed approximation functions to approximate the physical properties of the ammonia-water coolant pair which are different from the previous literature [P2, P4, P6].
    b. I investigated the effects of seven significant operating parameters (temperatures, concentrations, efficiency of the heat exchanger) of the mathematical model, and found that the energy consumption cannot be significantly reduced by the help of changing these parameters [P3, P5, P7].
    c. I found that the way of the reduction of the energy consumption of ammonia-water absorption cooling circuit is the replacing of the electric solution pump.

2. I have created a novel model of a hot air engine with a construction different from those found in the literature [P8, P10], in the framework of which:
    a. During the examination of the theoretical model, I verified that the specific energy consumption of the new construction is more efficient than that of traditional types.
    b. I made the prototype of this novel hot air engine. With the help of the experimental examinations, I determined the pressure curve of the novel engine, with the help of which I validated the theoretical model.

3. I created a theoretical model of a new type of pump working with steam to replace the solution pump of the ammonia-water heat pump circuit [P9]. In this context:

a. I created the mathematical model of the new type of steam pump. Based on the model calculations, it can be concluded that its specific performance is significantly better than that of the hot air engine, and its operating frequency is greatly affected by the heating and cooling temperature.
b. Based on the completed prototype, it can be stated that the construction works on a self-starter basis, it starts independently without an external energy source.

7. OPTIONS OF DEVELOPMENT

In this dissertation, starting from the absorption heat pump and the modelling of the physical properties of this system and its working fluid, I have defined the direction of the research. By examining the model of the heat pump, I looked for solutions to increase its efficiency. I aimed to develop a system that is independent of electrical energy. For this, I had to find a solution for the circulation of the working fluid. I gave two possible answers, i.e. two heat engines capable of utilising low temperature heat sources.

These two possible machines can do more than solve the basic problem. The new type of heat engine is a fairly efficient machine, suitable for example for operating circulating pumps, or even for pumping wells, or even for small power generation functions. A physical model was also produced, which worked as expected, but also helped to identify a number of problems. A motor with higher compression ratio and higher base pressure is needed. However, this requires different materials.

The machine with steam working fluid shows beyond this, as it can also operate with extremely low temperature range heat sources, which can be chosen almost freely, if it is filled with a suitable working fluid charge. In addition, it can also perform control functions, for example as a pump for a solar collector system or a cooling water circulation system, which are electrically driven and controlled. Moreover, both machines are so simple that they could have been built in ancient times. Of course, both machines require a lot of further improvements before they can be used in practice.

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