THE THERMO-FLOW PROCESSES PROCEEDING DURING THE TWO – PHASE FLOW IN SUPERSONIC EJECTOR APPLIED IN LOW POWER SOLAR AIR CONDITIONING SYSTEMS

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ABSTRACT

In the paper, the selected designing problems which can result from using the supersonic two-phase flow steam (R 718) ejector in low power refrigerating systems where the high heat source is solar energy have been presented. The numerical calculations were carried out using finite element method in ANSYS CFX software and the mesh was generated using ANSYS ICEM. In order to validate the numerical results a special set-up was designed and constructed. A series of experiments was carried out at the entrainment ratio in range from 0 to 0.3. During the experiments temperature and pressure of primary (motive), secondary (induced) and outlet stream were measured. The experimental results were validated with the numerical calculations. For boundary conditions and SST model of turbulence applied for calculations the numerical results showed a good agreement with the data obtained during experiments.

1. INTRODUCTION

The solar collectors are the popular part of hot water installations. The increasing production of highly developed collectors created a possibility to use them in more advanced thermal systems like heat pumps or air conditioning systems. Both applications are widely described in literature on absorption and ejector systems. The authors selected water (R 718) as a refrigerant in the ejector appliance for the sake of the special thermodynamic properties. An essential issue of the ejector's refrigeration system and the solar collector cooperation (shown in Figure 1) is a correct match of a steam generator temperature level. Optimally selected temperature of a steam generator causes the maximization of the cooling effect of the solar air – conditioner. The typical problem of the low power ejector is a nozzle geometry. For the low pressure of the primary stream essential outlet diameter value of the primary nozzle can exceed the diameter value of a mixing chamber. Such combination of diameters can make it impossible to draw in the medium from the evaporator. Figure 1. The diagram of the devices and heat exchangers of the ejector unit and the occurring processes on *lg* p-h diagrams.It was shown that the low power ejector needs non-standard design procedures (Kasperski and Pietrowicz, 2006), e.g. modeling of processes using the finite element method.Water as the ecological working medium has many advantages: high heat of evaporation, high specific heat, it is not chemically aggressive, not dangerous to people and its general availability and low price is conductive to use. However, there are also disadvantages such as: under atmospheric pressure of work, low volumetric capacity, freezing at minus Celsius degree, absorption of big amount of gases. In the last few years in the ejector refrigerating cycle the modern refrigerants from the fluorhydrocarbon groups are used with significant success. Their advantages are: high pressure of work, high refrigerating capacity, among drawbacks we can list: danger to people and high price. For ejector cycles important is that for water as the refrigerant the diameters of nozzles are bigger than 1 mm, when for the other refrigerants the diameters are smaller than 1 mm which makes the nozzles production technologically difficult or impossible. For that reason applying water in the systems of refrigerating capacities up to several kW is more favorable.Figure 2. The design of internal device construction and an example of installation on the roof slope The analysis of technological possibilities of the solar collectors made by a cooperating producer allowed to develop the conception of a simple construction air conditioning unit which was based on water-ejector cycle, where steam was generated in a flat solar collector. The concept design of the solar air-conditioner unit is shown in Figure 2. The construction of the device was based on a flat heat exchanger. It was assumed that the device will have a simple, compact construction which does not need skilled assembly and special devices during installation. The installation in a skew hipped roof end should be similar to assembly of standard roof windows. The sprinkling evaporator of large volume with a filler was used in the refrigeration system, for the forced fluid flow circulation the low power consumption pump was installed.

2. EJECTOR SYSTEM

A simple, classical ejector consists of three basic elements (Figure 3) – primary nozzle called also motive nozzle, secondary (induced) nozzle, mixing chamber. Primary nozzle is convergent-divergent element in which the working fluid expands from the steam generator pressure to suction pressure and the velocity increases from zero to the values exceeding a few times Mach number. In the throat of primary nozzle the parameters reach the critical values. Then expanded motive stream draws from the space (2) working fluid called secondary stream at the value of pressure p_2 and temperature t_2. Both streams flow to mixing chamber. At the final stage of the process pressure in diffuser increases to p_3 and velocity decreases to w_3, which is much smaller than the sonic speed. For this reason that part of ejector is called the subsonic diffuser.The parameter characterizing the quality of ejector is entrainment ratio – *ER* – the ratio between the amount of mass flow ratio of the induced stream and the amount of mass flow ratio of the motive stream .

(1)Even for the best ejectors working in very beneficial system of cycle parameters the entrainment ratio does not exceed unit.

Figure 3. The scheme of the supersonic small power ejector with the distribution of pressure and Mach number along symmetry axis of the device

3. NUMERICAL MODELING

The physical processes occurring in the ejector can be described using the continuity, Navier – Stokes and energy equations (Alexis and Rogdakis, 2003 and Bartosiewicz *et al.,* 2005). The system of three equations was solved in commercial ANSYS CFX 11.0 software using the finite element method technique.The device which was subjected to the numerical analysis is shown in Figure 4a. The domain of calculations consisted of the parts described in section 2. Assuming that the flows occurring in the ejector are axisymmetric the numerical calculations were simplified to the ejector sector shown in Figure 4b.

Figure 4. The main elements of the analyzed ejector; a) the physical model, b) the simplified numerical model with the applied boundary conditions

The analyzed domain of calculations was meshed using the 4986 elements: 245 elements of wedge type and 4741 elements of hexahedra type. The mesh was generated in ANSYS ICEM 11.0 software. Additionally, in the places where the high pressure and temperature gradients were expected - very near the walls and in the outlet surrounding of the primary nozzle - the mesh was thickened. The details of the structured mesh were shown in Figure 5.

Figure 5. The details of the mesh applied in numerical calculations; a) the motive nozzle with the part of the induced nozzle, b) the middle part of the ejector – the mixing region of the two streams, c) the outlet of the ejector

In the numerical domain the following boundary conditions were assumed (Figure 4b):- the main inlet is the *inlet* type condition at given saturated temperature of steam and the value of mass flow rate;- the side inlet is the *inlet* type condition at given saturated temperature of steam and the value of mass flow rate;

- the outlet is the *outlet* type condition at given average absolute pressure;

- at the walls of ejector - the *adiabatic wall without slip* type condition;

- at the side-surfaces in respect of axisymmetric form of the fluid fow the *symmetry* type of conditions were applied.

The working medium was the steam (R718), whose properties were calculated on the basis of the model of steam called IAPWS-IF97 (Wagner and Kruse**,** 1998) proposed in ANSYS CFX 11.0 software. It was assumed that the steam supplied to primary and secondary nozzle was saturated and the quality of steam equaled x = 1.Very important for the flow processes is using the correct turbulence model. Comparing the numerical results with the experimental data Bartosiewicz *et al.* (2005) proved that one of the best models of turbulence is the model called *SST - the shear stress transport*.

4. EXPERIMENTAL SET-UP

In order to validate the results obtained from the numerical calculations the special set-up was designed and constructed. The set-up was dedicated to research the two-phase thermal flow in the steam ejector. The scheme of set-up is shown in Figure 6. Instead of the solar collector the electrical steam generator with the heater regulated by the autotransformer (maximum of power 900 watts) was used. The steam was produced at saturated conditions. Another very similar, regulated heater was installed in a pump circulation of an evaporator (2). The maximum power was lower than that in the steam generator and reached 300 W. Instead of the air cooling evaporator the water cooling system (3) was used. This solution is more independent of temporary ambient temperature in laboratory. During the experiment temperature and pressure of the inlet steam and the outlet steam were measured. The suction pressure of the secondary stream very near the outlet of the primary stream was gauged. Temperature of the liquid in the evaporator cycle was measured on the section before the circulation pump. The volumetric method was applied to determine the values of the steam mass flow rate. For this purpose the level indicators were placed near the steam generator, evaporator and condenser. During volumetric measurements lower line of the liquid was separated by the valves from the steam generator, evaporator and condenser. The pump supplying the steam generator was switched off during the experiment.

Figure 6. Experimental set-up of the two-phase refrigeration ejector system In the set-up there were installed: the primary nozzle of the ejector (made of brass,

Figure 7 d) with the 10° cone and the critical diameter 1.8 mm, the secondary nozzle (Figure 7 b) with the diameter of the mixing chamber 6.1 mm and the transparent plastics, which will be necessary for the visualization research. The parts of the set-up with the assembled ejector, the mixing chamber and the details of the motive nozzle are shown in Figure 7.

Figure 7. The set-up: a) the general view, b) the details of the assembled ejector, c) the mixing chamber d) the primary nozzle

The design criteria of the ejector were decided as follows: pressure of the primary steam (47,4 kPa) corresponding to the boiling temperature +80°C, temperature of condensation +35°C, temperature of evaporation +15°C. The research of the ejector consisted of the measurement series at constant power of the steam generator and at different power of the evaporator ranging from 0 to 150 W. On the basis of changes in the level indicator the entrainment ratios were determined. At the same time of the experiment the following parameters were monitored: pressure and temperature in the steam generator, condenser and evaporator.

5. NUMERICAL RESULTS AND THEIR VALIDATION

The numerical calculations were carried out for the designing criteria of the ejector at the entrainment ratio in the range from 0 to 0.3. After a series of calculations the three-dimensional distribution of several parameters was obtained. The examples of numerical calculations of Mach number, quality and streamline of steam at the different entrainment ratios are shown in Figure 8.

Fgure 8. The numerical results of selected parameters at the entrainment ratio *ER* = 0.00, 0.10, 0.20, 0.30: a) Mach number, b) quality, c) streamline

Additionally, in Figure 9 it is shown how the pressure (9a), Mach number (9b) and quality of steam (9c) at the different entrainment ratios along the symmetry axis of the ejector were changing.Figure 9. The selected values along the symmetry axis of the ejector a) Mach number, b) pressure from the primary nozzle outlet c) quality of steam One of the parameters very useful for validation of the numerical results (correctness of the applied boundary conditions and the turbulence model) was the secondary (induced) pressure. Its value is a function of entrainment ratio and indirectly the pressure occurring after the primary nozzle outlet. This pressure depends on the applied boundary conditions and the turbulence model. In Table 1 there were shown the selected values obtained from a series of experiments, additionally the numerical values of induced pressure were inserted and errors/measurements were compared.

Table 1. The comparison of the experimental data with the numerical results. Pos set-up experiment numerical modeling Comparison
steam generator Evaporator condenser entrainment ratio evaporator Evaporator
p_1 t_1 p_2 $t_{2''}$ p_3 $t_{3''}$ p nm
kPa °C kPa °C kPa °C [-] kPa kPa %
1 47,4 80 0,95 6,2 5,7 35,2 0 0,963 0,013 1,4

2	0,9	5,4	0	0,963	0,063	7
3	1,65	14,5	0,15	1,623	0,027	1,6
4	1,35	11,4	0,1	1,367	0,017	1,3
5	1,45	12,5	0,1	1,367	0,083	5,7
6	2,45	20,7	0,3	2,603	0,153	6,2
7	2,4	20,4	0,3	2,603	0,203	8,5
8	2,8	22,9	0,3	2,603	0,197	7
9	1,8	15,8	0,2	1,914	0,114	6,3
10	1,9	16,7	0,2	1,914	0,014	0,7
11	2	17,5	0,2	1,914	0,086	4,3
12	1,25	10,3	0,05	1,147	0,103	8,2

The induced pressure values in the suction space were obtained during the experiment and as the results of numerical calculations shown in Figure 10.

Figure 10. The induced pressure as the function of entrainment ratios, the comparison of the numerical results (in blue) with experimental data (in red)

6. CONCLUSION

In this paper the concept of the solar air conditioned ejector device was presented. The special set-up was designed and constructed for observation and measurement of the two-phase flow physical processes in the ejector cycle with water as the a refrigerant. The temperature levels of the air conditioner in particular heat exchangers were assumed to be +80/+35/+15°C. A series of measurements was carried out.For the values obtained from the experiment the numerical analysis of the thermal flow processes occurring in the ejector was performed.On the basis of numerical calculations there were indicated mutual relations of several important use parameters of the model ejector. The numerical results proved a good agreement with the experimental data. The comparison of measurement values of induced pressure with numerical results showed that for the tested range of entrainment ratio the error contained in limits 0.7¸8.7 %.Presented method can be helpful in numerical matching of ejector geometry without necessity of constructing the prototypes. The authors proved that it is possible to perform numerical modification of the ejector geometry or working conditions, especially in case of the work conditions difficult to obtain in laboratory.

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