Abstract

This paper presents numerical analyses for the study of the ejector nozzle of a solar aided ejector-based air conditioner system which uses water as working fluid. Analyses of steady-state computational fluid dynamics (CFD) were conducted in order to corroborate and optimize the results of previous one dimensional studies in a three dimensional simulation. Several valuable discoveries were found through the simulation: Optimal conditions of geometry for known mass flow rates and temperatures were found; different dimensions of the nozzle were found as optimal for the same conditions proposed in previous literature; it was also proven that geometries and initial conditions, proposed in other literature, don’t always yield physically reasonable results.

Keywords: Ejector, Nozzle, Design, Solar, Simulation, Air Conditioner.

1. Introduction

The current work is focused in a solar-assisted ejector cooling system for air conditioner, in order to replace conventional compressor based air-conditioner systems which consume much more energy [1]. The main point of study will be the ejector, with special attention on the nozzle through parametrical analysis of geometries and initial conditions, aided by numerical analysis and 3D simulation analysis based on previous literature [2], [3] with the objective of corroborating this results previously obtained and also proposing new conditions and geometries. The numerical analysis and simulations are done with the software Ansys® CFX 12.1, using three-dimensional simulation. For working fluid, water has been chosen, because its “green” inexpensive and readily available for practical and experimental uses.

*Corresponding author
2. Description of the System

The whole system consists in 2 closed circuits: The solar collector circuit and the Air conditioner circuit. The scheme of the system is shown in Figure 1. In the first circuit the thermal energy from the sun is obtained and then transferred to the second circuit where the cooling occurs. In this study we’re focused more in the air-conditioner part of the system, specifically in the Ejector and it’s nozzle. The parts of the system are:

![Solar Aided Ejector Air-Conditioner](image)

Figure 1: Solar Aided Ejector Air-Conditioner

A. Solar Collector Circuit

- Collector: In this phase, thermal energy is acquired from solar radiation, and is circulated along the sub-cycle through a working fluid
- Storage Tank: The working fluid from the collector is stored in this adiabatic tank in where the flux is controlled, in order to transfer the necessary and/or required heat to the generator of the air-conditioner circuit

B. Air Conditioner Circuit

- Generator: In this part of the system heat is transferred to the air-conditioner circuit in order to provide the working fluid (water) with energy and make it run to the next step, which is the Ejector.
- Ejector: This is the main part of study of this paper, and it’s used to generate cooling power as the compressor in the conventional air conditioners. It has 2 inlets and 1 outlet, and consists of 4 main parts: the nozzle, the vacuum chamber, the mixing chamber and the diffuser, which are arranged as shown in Figure 2. The first inlet is fed by the generator, the second by the evaporator and the outlet feeds the condenser. The working fluid transformed in steam passes through the ejector’s nozzle and is speeded up generating a vacuum at the exit of the nozzle in order to induce evaporation and entrain steam from the evaporator; thus, both steams are mixed in the mixing chamber and then conducted to the diffuser where are slowed down thus the pressure increases, conditions which help the condensation, that is the next step
• Condenser: the water that has been previously transformed into steam, is taken back to liquid again by means of heat exchange with the environment. Then the water is conducted to both the Evaporator and the Generator.

• Evaporator: The evaporator is fed with water coming from the condenser after being passed through a check valve, and feeds the Ejector with evaporated water, at the second inlet of the Ejector located at the vacuum chamber. In this phase of the process is where the cooling of the environment occurs.

3. Simulation Software

To build the geometry, SOLIDWORKS® 2009 was used. The simulation software is the CFD package offered by Ansys© 12.1, namely CFX®. CFX is capable to solve heat transfers and fluid problems, and also supports supersonic fluids which are one of the most important requirements for this study.

4. Methodology

A parametrical analysis was carried out, consisting in an iterative process of evaluation of 3D steady state analysis for the ejector, nevertheless, the study focuses specially in the design of the nozzle, which is a key component of the ejector. First the whole ejector was tested with the dimensions for the nozzle named “Set 0” in Table 1. The drawing of the ejector tested in this first simulation is shown in figure 2.

Then, the Nozzle was tested separately; several geometries were tested. The drawing of the generic nozzle is shown in Figure 3 and the dimensions tested are shown in Table 1.
TABLE 1. Dimensions of the Nozzle Tested (MM)

<table>
<thead>
<tr>
<th>Geometry</th>
<th>D_{Nozzle exit}</th>
<th>D_{Nozzle throat}</th>
<th>D_{Nozzle inlet}</th>
<th>L_1</th>
<th>L_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 0</td>
<td>19.8</td>
<td>6</td>
<td>22.6</td>
<td>33.5</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 1</td>
<td>19.8</td>
<td>6</td>
<td>22.6</td>
<td>102.1</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 2</td>
<td>22.6</td>
<td>6</td>
<td>22.6</td>
<td>64</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 3</td>
<td>22.6</td>
<td>5</td>
<td>22.6</td>
<td>64</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 4</td>
<td>16.5</td>
<td>5</td>
<td>22.6</td>
<td>64</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 5</td>
<td>8.2</td>
<td>5</td>
<td>22.6</td>
<td>17.7</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 6</td>
<td>7.6</td>
<td>5</td>
<td>22.6</td>
<td>14.5</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 7</td>
<td>7.6</td>
<td>5</td>
<td>22.6</td>
<td>14.5</td>
<td>51</td>
</tr>
<tr>
<td>Set 8</td>
<td>7.6</td>
<td>5</td>
<td>39</td>
<td>14.5</td>
<td>51</td>
</tr>
<tr>
<td>Set 9</td>
<td>6.5</td>
<td>4</td>
<td>22.6</td>
<td>14.5</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 10</td>
<td>8.3</td>
<td>6</td>
<td>22.6</td>
<td>14.5</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 11</td>
<td>9</td>
<td>7</td>
<td>22.6</td>
<td>14.5</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 12</td>
<td>9.5</td>
<td>7.5</td>
<td>22.6</td>
<td>14.5</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 13</td>
<td>10</td>
<td>8</td>
<td>22.6</td>
<td>14.5</td>
<td>39.6</td>
</tr>
<tr>
<td>Set 14</td>
<td>10.7</td>
<td>9</td>
<td>22.6</td>
<td>14.5</td>
<td>39.6</td>
</tr>
</tbody>
</table>

Figure 3. Diagram of the Nozzle.
5. Settings and Assumptions for the Simulation.

Steady-state simulations are performed. The following assumptions were done:

- All the walls of the device are assumed as adiabatic.
- The mass flow feed from the generator and evaporator is assumed as continuous, that is, constant in time.
- It’s assumed that the conditions at the inlet of the nozzle are controllable in terms of temperature and flow mass rate.
- As the working fluid of the whole system is water, “water as an ideal gas” was chosen from the library of materials of the program, for the simulations.
- In real life a mixture of steam and air occurred, nevertheless for practical effects it’s assumed that in the whole system only exists water vapour.
- The analyses are focused in the ejector’s nozzle, and in the ejector, due to this there is not any analysis regarding the type of solar concentrator or the energy required for this case, therefore, the conditions for generator are assumed as achievable.
- Inlet conditions: Mass flow rate desired is 0.006 kg/s [2] at the nozzle’s inlet, and was tested from 0.004 to 0.008 Kg/s. The Temperature varied from 100 to 130°C depending on the case. For the first case the second inlet was taken as 0.002 kg/s with a temperature varying from 10 to 20°C[2]. In both cases turbulence was selected as “Medium” with a conservative intensity of 5%.
- Outlet conditions: for the first case was set with a pressure among 0.8 to 1 atm; and in the second case, when it’s the sole analysis of the ejector’s nozzle it was set as “supersonic”

6. Results and Discussion.

In our study Maximum Pressure and Minimum Temperature are critical parameters which would tell the feasibility of the analyzed system. Therefore a Temperature lower than zero would be undesirable due to the risk of freezing. In the extreme case of a value much lower than zero would indicate a mathematical solution that is not physically attainable. Moreover, a Pressure over 2 atm would be unpractical to achieve, so a pressure lesser than 2 atm is desired. The other critical parameter is the nozzle, which main objective is to accelerate the fluid until a supersonic velocity is reached at the exit of it. Thus, the whole ejector wouldn’t work if there’s any shock wave somewhere before the exit of the nozzle. Then any design which at the conditions required doesn’t reach supersonic fluid is dismissed.
An abstract of the results obtained in the simulations for the nozzle is shown in Table 2, containing the corresponding settings, the nomenclature of the geometries are referred to Table 1 and Figure 3. In this table only the critical values are shown, which are; Maximum Pressure, Minimum Temperature, Maximum Mach Number and Maximum Velocity.

The very first simulation consists in the simulation of the whole ejector. After obtaining the results of the simulation even with different parameters and inputs, it was found out that the results expected weren’t obtained due to a shockwave in the nozzle. For this simulation it was found that only an extremely high flow mass ratio would prevent the shockwave in the nozzle, result that is not only unpractical, but also results in illogical values of pressure and temperature. These illogical values could be interpreted as a change of phase in the working fluid.

The dimensions of the nozzle were changed in the next experiments which are shown in Tables 1 and 2, the dimension changes mostly consist in modifying the exit diameter, the length from the throat to the exit and the diameter of the throat. For the first time that the supersonic fluid was reached at the exit, the conditions were as shown in simulation 7 in Table 2; however, the results obtained in this simulation were still illogical in matter of temperature, getting some extremely low temperatures below zero; thus more modifications were done until an optim result was obtained. Another problem found is that a pressure some times greater than 5 atm at the initial chamber was needed in order to reach the supersonic flow at the nozzle’s exit.

As the throat’s diameter was increased better results were obtained, lesser pressure was required at the initial chamber and the lower temperature was in some cases still under zero but not less than -5C which is not an impossible or unreal value. However as the diameter of the throat was being increased the minimum mass flow required in order to achieve supersonic fluid was greater, but not in an exaggerated way.

The best results, and by any meanings more approached to reality are Simulations 18, 19 and 20 from Table 2. In figure 5 the graphic results of simulation 19 are shown.

In figure 4 the first simulation is shown, and in figure 5 the results for simulation 19 (see table 2 in next page) are shown where one of the best design for the nozzle is shown.
7. Conclusions

Aided by software simulation it was found out that the first geometry tested, which was proposed by previous literature, resulted in an early shockwave inside the nozzle of the ejector.

For the problem studied with a mass flow between 0.006 Kg/s to 0.008Kg/s with an inlet temperature of 110° C it was found an optimal range of throat diameters which varies from 7mm to 8mm, with an exit diameter of 9mm to 10mm having a distance between throat and diameter of 14.5mm. A very narrow nozzle’s throat would produce supersonic velocity with less mass flow rate, but it also would require a considerable increment in the pressure to achieve it.

The design of the nozzle is very delicate and its key components are the throat and exit diameter the ratio and the distance between them. For the conditions studied where the inlet mass flow rate, varies between 0.006-0.008Kg/s and for a distance throat-exit given (14.5mm), having a ratio DNozzle throat/ DNozzle exit less than 0.6, (when DNozzle throat varies between 5mm and 9mm) wouldn’t result in a supersonic flux, then the whole ejector wouldn’t work.
For a given fluid, another key factor for achieving supersonic velocity is the relationship between mass flow rate and the Nozzle Throat Diameter. So in the case that the flow of the system is adjustable, the narrowness of the throat should be adjustable as well, in order to achieve always the supersonic velocity at the exit.

Temperature behaves in the following way: for a given throat diameter and flow mass rate the temperature obtained during acceleration will be reduced more as Temperature from the generator is lower. This could be troublesome in real life, because we could face a change phase issue if the temperature is too low. Also a high temperature at the inlet contributes to have a higher velocity in the system.

Future works could study, aided with simulation software, the next steps of the ejector that would be the effect of the flow out of the nozzle in the entrainment flow from the evaporator. Afterwards a study of the mixing and behaviour in the diffuser could be done. Also is advised to do a phase change simulation analysis, due to the possibility of its occurrence in the areas of higher velocity in the nozzle. Another improvement to this work would be to use air mixed with steam which is what in real life would occur.

ACKNOWLEDGMENT

Thanks to Kun Shan University of Technology.

References


