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A MODEL FOR THE OPTIMIZED CONTROL OF AN INNOVATIVE AIR CONDITIONING SYSTEM WITH VARIABLE GEOMETRY

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ABSTRACT

In this work it was aimed to develop and optimize an artificial neural network (ANN) which accurately simulates ejector cooling cycle performance according to the operational conditions. It would also allow for the control of a spindle, located in the primary nozzle, in a way that ejector performance is maximized. First, it was aimed to optimize an ANN capable to accurately simulate the performance parameters of a refrigeration cycle and the ejector performance itself. Input variables were the operational conditions of the cycle. In this first stage, a data set with some limitations in terms of input variables domain representativeness was used including those cases that resulted in ejector failure. With this first data set it was possible to evaluate the effect of those limitations in the artificial neural network optimization. In the second stage, a new data set was presented to the selected ANN in order to assess the influence of each input parameters on the cycle performance and also on optimal spindle control. The condenser temperature was found to be the most important parameter affecting the ejector performance and so the control of the spindle position brings great advantages for optimizing the cycle performance in order of the operative conditions.

Keywords: Refrigeration, ejector system, variable geometry, artificial neural network, optimization.

1. INTRODUCTION

Air conditioning and refrigeration equipments have a growing impact on the increasing energy consumption observed over the last decades. The use of alternative energy sources, such as solar energy, allows a reduction in the impact caused by those systems using electricity that is essential to the actual World's energy scenario [Chen et al., 2013]. Ejector refrigeration is a promising alternative to the conventional vapor compression refrigeration systems and it has been gaining considerable attention. Ejector cooling is a thermally driven cycle that can use solar energy as power source and thus its performance is very dependent on environmental conditions. The use of a new feature in the ejector, a spindle, allows for controlling the ejector performance depending on operating conditions, by varying its position [Varga et al., 2009].

2. EJECTOR OPERATION

An ejector is usually composed of four main parts: a convergent-divergent nozzle (primary nozzle), suction chamber, constant area section and a subsonic diffuser [Chen et al., 2013]. Figure 1 depicts the schematic cross section of a conventional ejector. The primary fluid coming from the generator at high pressure enters into the primary nozzle (P) of the ejector. Expansion of the working fluid through the divergent part of the primary nozzle creates a zone of low pressure and high speed (Mach> 1) at the exit plain (ii). The secondary fluid coming from the evaporator (S) is then drawn into the suction chamber due to low pressure caused by the primary fluid. Due to the great difference between the velocities of the two streams, they form a shear stress layer between the primary and secondary fluids and the secondary fluid gets accelerated to sonic velocity (iii). This condition is often called as double choking. From this point on, the two streams start mixing until their velocity levels (iv). The location of the mixing section depends on the operating conditions and geometry of the ejector but should ideally take place somewhere in the area of constant section or the beginning of the diffuser. After mixing, the flow becomes subsonic due to a transverse shock (idealised case). In the subsonic diffuser, the mixed stream is decelerated and recompressed. The outlet pressure depends on conditions in the condenser of the refrigeration cycle determined by the condensation temperature [Varga et al., 2009].

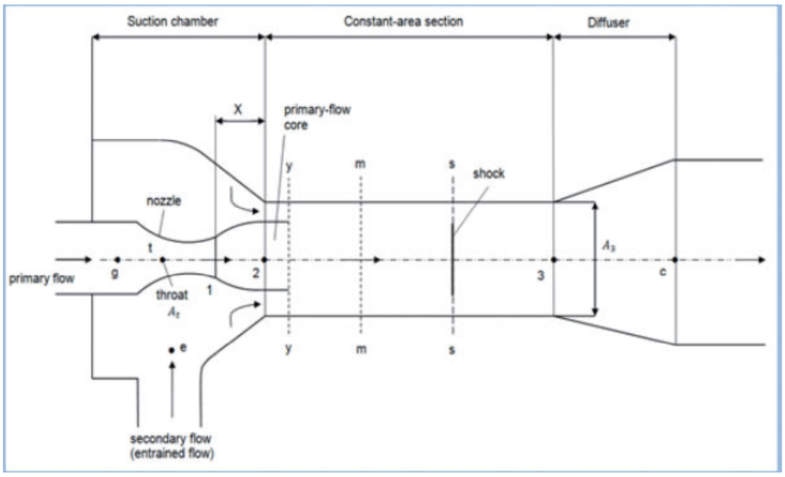

Figure 1. Ejector cross section

The performance of a refrigeration cycle, such as the ejector refrigeration cycle, is often measured by the coefficient of performance (COP) defined as:

$$COP = \frac{\dot{Q}_e}{\dot{Q}_g + \dot{W}_b} \tag{1}$$

where $\dot{Q}_e$ and $\dot{Q}_g$ are the evaporator cooling and the generator capacity, respectively, and $\dot{W}_b$ is the pump work.

As the pump work is usually negligible (typically represents less than 1% of the energy introduced into the generator), it is usually neglected in calculating the COP.

In ejection cycles, other performance indicators such as entrainment, expansion and compression ratios can be defined to characterize the cycle. The entrainment ratio is defined as the ratio between the secondary and primary mass flow rates as:

$$\lambda = \frac{\dot{m}_e}{\dot{m}_g} \tag{3}$$

The relationship between the entrainment ratio and the coefficient of performance is given by the following equation [Chen et al., 2013; Lebre, 2011; Zhu et al., 2009]:

$$COP = \frac{\dot{Q}_e}{\dot{Q}_g} = \lambda \frac{\Delta h_e}{\Delta h_g} \tag{4}$$

being Δh_e and Δh_g the enthalpies of vaporization in the evaporator and the generator, respectively.

The operating pressures/temperatures of the generator, condenser and evaporator significantly influence the performance of the refrigeration cycle. In general, the COP increases with the temperature of the generator and the evaporator, while decreases with condenser temperature. Ejector dimensions should be optimized according to the operating conditions. Deviations from design conditions usually lead to a significant reduction of the ejector performance. For example, an increase in the temperature of the generator will result in increased primary flow rate while the secondary flow rate remains unchanged and thus it results in a reduced COP and λ. In order to take advantage of the increased energy in the generator, the geometry of the ejector should change, e.g. by decreasing the primary nozzle diameter [Varga et al., 2009]. Detailed discussion of the dependence of ejector geometry on operating conditions can be found in [Varga et al., 2013].

Experimental studies have demonstrated that for a given set of operating conditions in the generator and the evaporator three distinct regions of operation curve can be identified, namely double choking, single choking and reverse flow regions. In the latter case, the ejector stops working, there is no cooling obtained in the evaporator.

When the ejector is operated below the "critical back pressure ", the cooling capacity and COP remain constant. Increasing the condenser pressure above critical prevents the secondary fluid to reach sonic velocity. When the secondary flow doesn't get choked, downstream pressure is transmitted upstream, resulting in a reduction in the flow rate of the secondary fluid and hence λ and COP. The flow rate of the secondary fluid will eventually vanish, the ejector stops working, the primary fluid will flow back to the evaporator (reverse flow).

3. OPTIMAL DESIGN OF EJECTORS

In order to make ejector cooling economically more attractive, several research works have been carried out in recent years with the objective to optimize the geometry of ejectors to achieve improved thermodynamic performance.

One of the geometric parameters that have the most effect on the performance of the ejector is the area ratio between the constant area section and the primary nozzle throat, r_A. In general, increasing r_A will increase the entrainment ratio and decrease the critical back pressure, so there should be an optimal value depending on the operating conditions [Varga et al., 2009]. However, there is a single area ratio that can be considered as optimal for each operating temperature both upstream and downstream the ejector [Varga et al., 2013]. To ensure that the cycle always operates optimally, would require a multi-ejector design, with different nozzle geometries, optimized for each temperature. Alternatively, a new and simple solution, a spindle, was proposed and tested (numerically and experimentally) by [Varga et al., 2009; Ma et al., 2010]. It is a movable spindle with variable section. The advance or retreat of the spindle will result in a change of the section area of the nozzle and hence lead to a change of the area ratio.

The position of the outlet section of the nozzle exit in the suction chamber, denoted by NXP, is another parameter that is known to affect both entrainment ratio and critical back pressure. It was shown that NXP forward to the mixing chamber reduces the COP and cooling capacity.

There is an optimal value for NXP which must be defined according to the operating conditions. An ejector with a mobile nozzle can improve the performance by having a flexible NXP. However there is still no consensus on optimal geometry possible for this component [Varga et al., 2009; Zhu et al., 2009].

The length of the section of constant area is normally not considered to influence the ratio of drag. However, recent studies have shown that the critical pressure of the condenser increases with the length of the section, allowing the ejector to operate in double chocking in a wider range of operating conditions [Kasperski, 2010].

Other solutions have been tested to improve the performance of the cooling system, in addition to looking for solutions that optimize the geometry of the ejector. Among them are the-pump systems. The pump is the most complex component of this system, requiring additional maintenance and electricity. Replacing it, these issues could be eliminated. Several projects have been conducted with this objective, such as the use hydrostatic head [Shen et al. 2005; Wang, 2009a], systems with two nozzles [Huang, 2006] or heat pump systems [Wang, 2009b].

4. MODELING THE OPERATIONAL CONDITIONS BY ANN

The ejector refrigeration cycle is an alternative to traditional cooling cycles primarily by its low cost and low environmental impact. The heat source to the generator may be supplied from industrial waste heat or solar thermal collectors. This work is based on the second case. An important limitation of solar energy is related to the availability of solar radiation, which varies throughout the day, depending on weather conditions. The cycle will only achieve optimum performance for certain solar conditions.

A solution to this problem is to optimize the geometry of the ejector to ensure that it adapts to the real scenario conditions, the COP of the refrigeration cycle is always maximized. One problem associated with this solution is the optimal position control of the spindle. To make a proper monitoring, a method that guarantees a quick response under any change for input variable is necessary. This method will produce new operational conditions for the ejector though appropriate changes of the position of the spindle for optimal position.

In order to control spindle position that results in optimal cooling performance for a given set of operating condition, a mathematical model is needed. Computational fluid dynamics (CFD) tools are commonly used for simulation of ejector flow, however, the prediction is too slow (long computational times) for control purposes. ANNs are able to give an almost immediate response and to accurately predict the system response to any change in the conditions of entry, ensuring optimal control spindle.

In this work it was aimed to develop and optimize an artificial neural network (ANN) which was able to accurately simulate ejector performance according to the operational conditions and such it would allow for the control of the spindle in a way that ejector performance is maximized. First, it was aimed to optimize an ANN capable to correctly simulate the performance parameters of a refrigeration cycle and the ejector performance itself. The artificial neural network simulated those parameters using as input values the operational conditions of the cycle. In this first stage, it was used a first data set with some limitations in terms of input variables domain representativeness and some input values will result in an ejector failure. With this first data set it was possible to evaluate the effect of those limitations in the artificial neural network optimization. In the second stage of this work a new data set was used. This data removed the former data set limitations. With this data set it was then possible to correctly optimize the artificial neural network.

Before starting the learning process of the neural network, it was necessary to choose the input variables for the process. It is intended that the neural network is able to simulate the relationship between the input variables, temperature in the condenser, evaporator and generator and position of the spindle; and output variables, ratio of drag and the COP, so that these variables can be optimized depending on the operating conditions.

The results showed that for present case with only a few input variables, several ANN configurations allow an accurate simulation of the refrigeration cycle performance. However, the configuration that obtained the best results was one which used the *Levenberg-Marquardt* learning algorithm, four nodes in the input layer, one hidden layer with ten nodes and an output layer with two nodes. The hidden layer used a sigmoid, while the output layer used a linear activation function. The condenser temperature is the most important parameter affecting the ejector performance and so the control of the spindle position brings great advantages for optimizing the cycle performance in order of the operative conditions.

5. RESULTS

5.1 Importance of variables

The Monte Carlo method has been used to understand the importance of each of the four input variables on the performance of the ejector system. A simulation a set of 5000 random number to each variable using an interval between their maximum and minimum values of each was performed. For this purpose, we used the random number generator Microsfot Excel (RANDBETWEEN function), which generates random numbers according to a uniform distribution. With the optimized ANN an analysis of the various parameters was made. This analysis focused on the understanding of the influence and weight of each parameter on the cycle performance. Figure 2 to Figure 5 show the influence of variables on the performance of ejector system measured by COP.

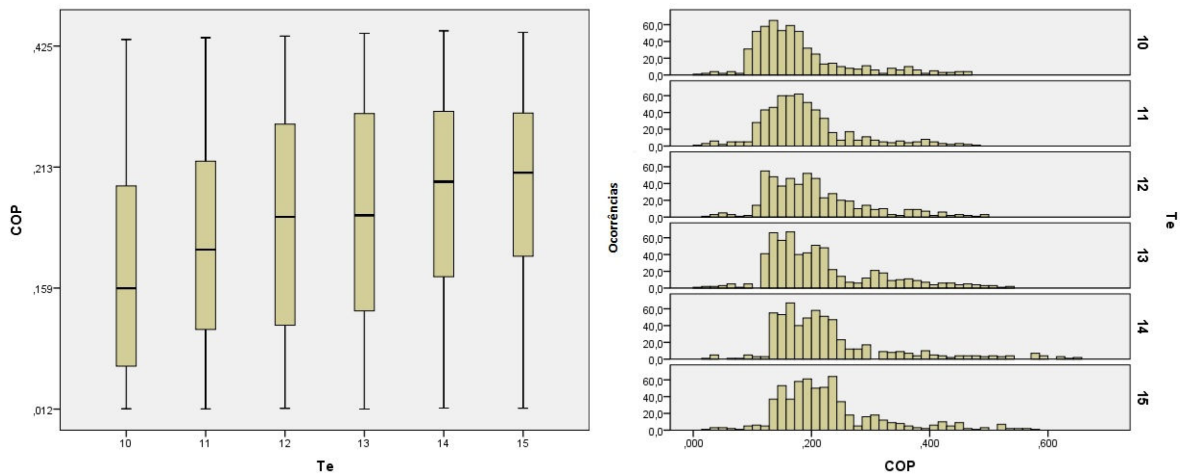

Figure 2. Variation of COP with the evaporator temperature (joint analysis considering the influence of other input variables): A - plot diagram, B - Histogram of occurrences

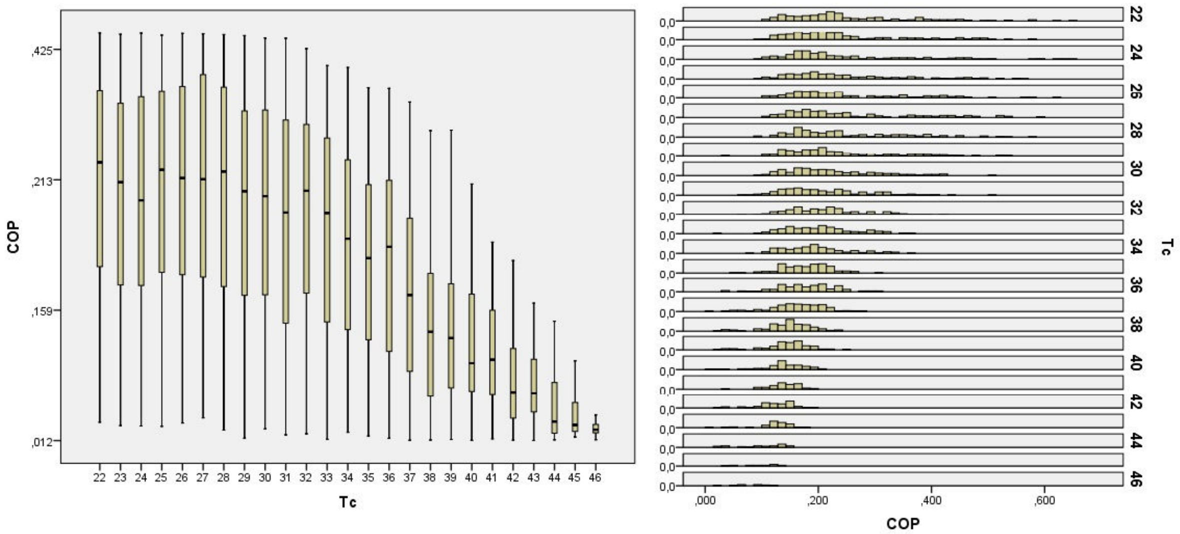

Figure 3. Variation of COP with the condenser temperature (joint analysis considering the influence of other input variables): A - plot diagram, B - Histogram of occurrences

In Figure 2 is possible to verify the effect of evaporator temperature on COP. There is an increase, although not very pronounced, of the average COP with an increase in the evaporator temperature.

Figure 3 shows that for the condenser temperatures above 40 ° C the COP hardly goes beyond 0,150, an already low value. The 46 º C, the maximum temperature considered, the ejector has practically can not operate and when it does, it does so with a performance very close to zero, so that ultimately there is no great practical interest in using these temperatures.

Figure 4 shows the variation of COP as a function of temperature generator. There is a decrease in the average value of this COP with increasing temperature. However, it appears also that regardless of the temperature of the generator is possible values higher COP, indicating that for each temperature of the generator is a set of optimum conditions which maximizes the value of the COP.

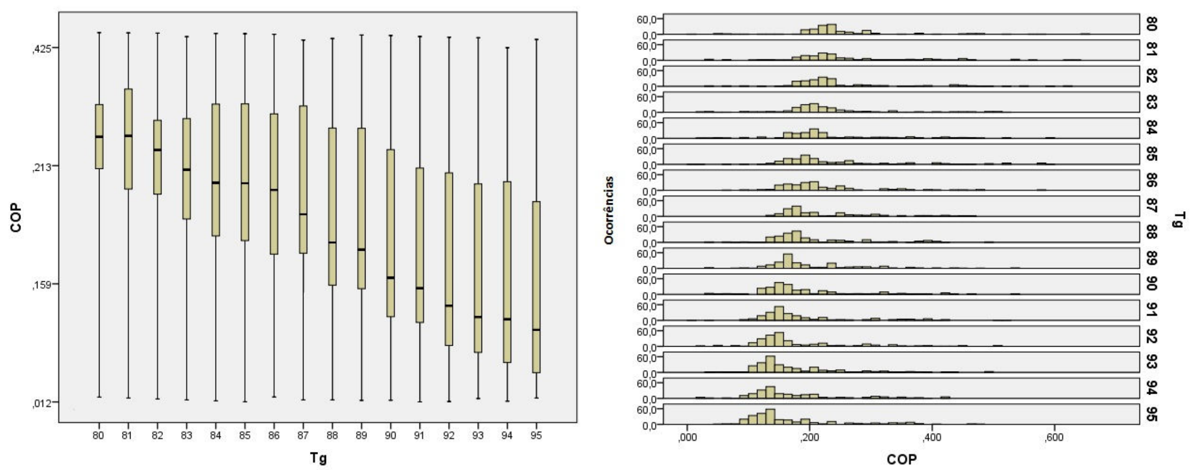

Figure 4. Variation of COP with the generator temperature (joint analysis considering the influence of other input variables): A - plot diagram, B - Histogram of occurrences

A simple analysis shown in Figure 5 confirms that the highest COP values are achieved for a spindle position of 1mm. The best performance is achieved at the positions of the spindle of 1mm, 2mm and 3mm. From the 7mm there is a stabilization of the average values of the COP and the influence of the COP have little or nothing can be seen in late position.

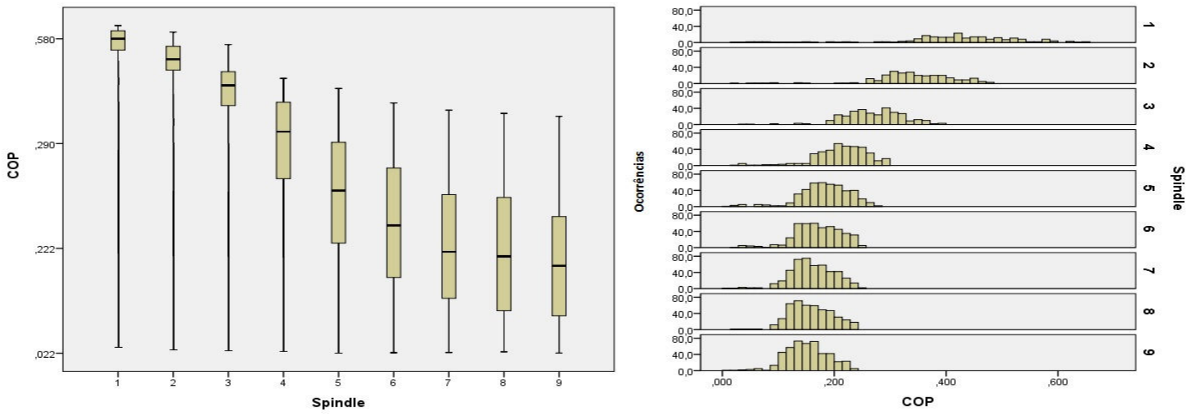

Figure 5. Variation of COP with the position of the spindle (joint analysis considering the influence of other input variables): A - plot diagram, B - Histogram of occurrences

5.2 Optimal ejector's performance using developed ANN

Using data from Monte Carlos simulations performed with optimal RNA it is possible to screen the operating conditions that maximize system performance. For this analysis, the sample results with COP upper than 0.250 were considered. In Table 1 the input values that optimize COP to values above 0.250 are shown. In the table it can see the highest possible temperature in each pair of condenser temperature of evaporator and generator. The values refer to each position of the spindle indicated for the maximum temperature of the condenser.

From the analysis of Table 1 it is possible to draw some conclusions. First, it is clear that the best performance of the cooling system is achieved in the first positions of the spindle for the entire field of temperatures. There is no case in which, to achieve the desired value of the COP, the benefit of having the ejector spindle away more than 5mm. The position of the spindle that ensures the highest COP may not be the most interesting location. For example, for an evaporator temperature of 12.5 ° C and a temperature of 85 ° C in the generator, has a higher COP value with the spindle 0.016 to 1mm. However with the spindle in position 2 mm achieves a higher maximum temperature of the condenser.

On the other hand, it was also observed that for higher temperatures in the evaporator, the position of the spindle will have a wider range of operation which can positively affect the performance of the cycle. In contrast, for the highest temperatures of the generator, the position of the spindle has benefits over a small range of positions. This behavior is in agreement with that expected by analyzing the functioning of the ejector. Higher temperatures result in generating the higher pressure of the primary fluid. With the spindle positioned so as to obtain a minimum area for the flow passage, its removal will lead to an increase in the flow of primary fluid and a consequent decrease in the COP, as the secondary fluid flow is maintained. The higher the temperature (and thus pressure), the spindle will have less effect in reducing the area occupied by the primary fluid.

Table 1 Values of input variables which optimize the COP to values greater than 0.250

Te [◦C]	Tg [◦C]	Tc max. [◦C]	Spindle [mm]	COP
10	80	26	1	0,440
		27	2	0,395
		30	3	0,298
		27	4	0,258
	85	28	1	0,393
		32	2	0,315
		33	3	0,271
	90	31	1	0,342
		32	2	0,296
	95	33	1	0,346
		35	2	0,267
12,5	80	27	1	0,472
		30	2	0,373
		32	3	0,349
		33	4	0,278
		29	5	0,262
	85	30	1	0,390
		33	2	0,374
		32	3	0,322
		35	4	0,262
		23	5	0,256

Te [◦C]	Tg [◦C]	Tc max. [◦C]	Spindle [mm]	COP
12,5	90	31	1	0,347
		34	2	0,334
		36	3	0,291
	95	33	1	0,339
		34	2	0,301
		35	3	0,285
15	80	28	1	0,395
		31	2	0,347
		33	3	0,301
		34	4	0,278
		34	5	0,259
	85	29	1	0,464
		33	2	0,371
		36	3	0,295
		36	4	0,264
	90	32	1	0,403
		35	2	0,319
		37	3	0,276
	95	34	1	0,416
		37	2	0,313
		36	3	0,256

5.3 Optimal spindle position based on auxiliary ANN

Having obtained the developed RNA for calculating COP and λ, there were some preliminary tests to obtain the optimal position of the spindle and which the gain that this process may bring to the performance of the cycle. Using the previously developed ANN a set of results is generated based on refinement of the process. These refined results are used to obtain a new auxiliary ANN to generate a set of optimal positions of the spindle. The behavior of the COP by increasing the condenser temperature for the various positions of the spindle is compared with the results obtained with the optimization of the position of the spindle using the auxiliary ANN. Figure 6 shows the simulated operating curves of the ejector for different spindle positions (1-9 mm). The Figure 6 also shows the optimal performance curve predicted by the auxiliary ANN (ANN opt). It can be seen that the ANN is able to foresee the optimal ejector operation with excellent accuracy.

It is clear that the " ANN opt " line follows the optimal points for each position of the spindle. The points which are to the left and below this line are ejector operating points, reaching its optimal value on the "ANN opt " line. Right above the line and the ejector will not work.

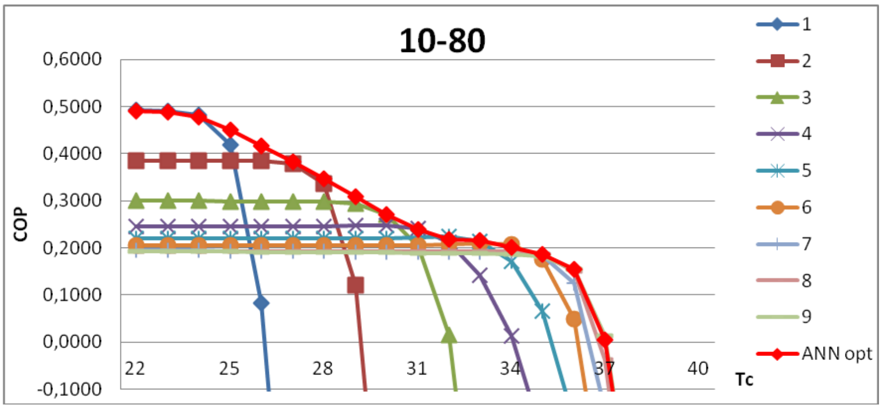

Figure 6. Evolution of the COP by increasing the condenser temperature for different positions of the spindle (1-9mm) for Te = 10 ° C and Tg = 80 ° C and compared with the results achieved with the use of auxiliary RNA that optimizes the position of the spindle.

6. CONCLUSIONS

The condenser temperature is a critical variable to be controlled. For set of operating conditions, this temperature will be increased to a critical value that will go into the ejector failure. Once the condenser temperature is very dependent on temperature, it is very important to optimize the operating conditions as a function of this temperature.

The change in the ratio of areas caused by the movement of the spindle will vary the performance of the system with the best values to be achieved in the positions between 1mm and 3mm. This range of influence may be extended depending on other operating conditions. Above 8mm cease to be any noticeable influence of the position of the spindle system performance.

The increase in the generator temperature in itself could lead to a decrease of system performance. However, the optimization of the geometry of the system to operating conditions of the generator will lead to gains in system performance instead of decreased performance that otherwise would. These are optimal conditions can be guaranteed by the correct positioning of the spindle. The use of a second RNA which optimizes the position of the spindle for operating conditions at that time is highly beneficial to system performance.

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