MODELING AND SIMULATION TRANSIENT OF THE ABSORPTION REFRIGERATION SYSTEM SIMPLIFIED USING AMMONIA-WATER MIXTURE

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Abstract. *In this paper, an absorption refrigeration system simplified will be modeled. This system is composed by the following items: generator, condenser, expansion valve, evaporator, absorber, reducing valve and a solution pump. The implementation of the model on transient regime on EES®, using Newton-Raphson iteration methods for solving the system of linear equations. The system was modeled using material balance for the ammonia-water solution; concentration balance for the ammonia species and energy balance . To complement the set of equations, closing equations were necessary, for example, the sum of concentrations of ammonia and water and the heat rate due to the fuel burning (heat of combustion). To solve the system some assumptions were necessary, for example, heat exchanges to the surroundings were considered very low for all components, except in condenser and material flows entering and leaving the apparatus was considered as one-dimensional. With the implementation of the initial conditions, obtains a data set, which analyzed, arrives at some conclusions as: the concentration of ammonia in the condenser and evaporator has stabilized at 90.53%; the ammonia concentration of the liquid leaving the generator was 31.61% and the absorber was 65.12% and the coefficient of performance instantaneous (COPI) reaches a maximum of 0.1722.*

Keywords: *Refrigeration, Absorption System, Ammonia-water, Simulation, Transient regime*

1. INTRODUCTION

Where climatic conditions are not favorable for a natural cooling, or the thermal load is very high, it needs a climate control artificial, with the use cooling equipment, which is available in various technologies, being the most utilized the system of the steam compression refrigeration, where electrical energy is used to drive a compressor. A technology that has already been very used is the refrigeration system by absorption, heat is the energy source. An absorption refrigeration system (ARS) is basically composed the following items: generator, condenser, expansion valve, evaporator, absorber, reducing valve and a solution pump (Fig. 1).

A feature of absorption systems uses a refrigerants mixture as working fluid. Generally, two substances are involved, where one of them works as a refrigerant fluid and the other as an absorber. Several mixtures are used as working fluid, and among them one can mention: ammonia-water, water-lithium bromide, water-sulfuric acid, ammonia-sulfocyanide (Cortez, 1994).

The absorption refrigeration system simplified (Fig. 1) under study, considers a solution of ammonia-water as working fluid. The ARS simplified consists of the following components: generator (GERA), condenser (COND), evaporator (EVA), absorber ABS), solution pump (SP) and two reducing valves.

The ARS has two levels of pressure: the highest level contemplates the following components: GERA and COND; and the lower level, where one find the EVA and ABS. The reduction valves and SB are elements make the reduction and pressure increased, respectively. Three different streams are found in the system: the first, with the flow of absorbent, composed by a solution of ammonia-water, where its concentration is modified in the GERA and in the ABS. The flow of absorbent occurs in the following components: GERA, pressure reducing valve (RV2), ABS and SP; the

second, with the ammonia flow with small concentration of water (primary coolant). This occurs in the following components: the top of GERA, COND, RV1, EVA and ABS; the third is the flow of water which will be refrigerated in the EVA, i.e., the secondary fluid of refrigeration.
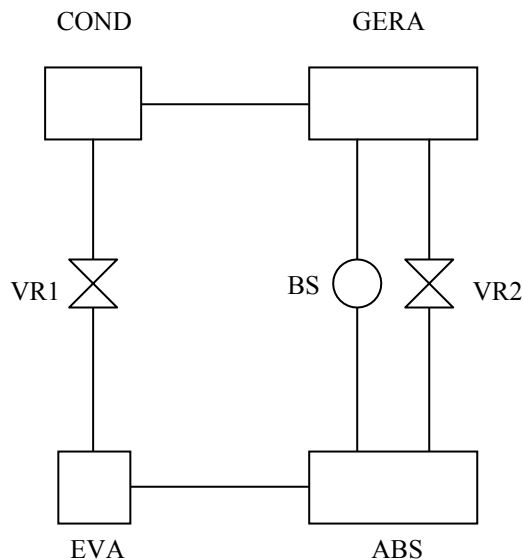

Figure 1. Schematics of the ARS.

Along the system, different thermodynamic states are encountered, these states are determined by at least three properties, for example, temperature, pressure and concentration.

The activation system is made by the heat flow which enters the GERA, coming from the burning of a fossil fuel the LPG (Liquefied Petroleum Gas). With the energy gain, ammonia, being more volatile, vaporizes from the solution and flows to the COND. Together with the ammonia vapor, there is steam, but only in small quantity. The mixture in vapor phase flows to the COND, exchange heat with the outside air, causing condensation of the mixture. At the exit of the COND, a solution of ammonia-water is a saturated liquid and has its pressure reduced in RV1, to the temperature and evaporation pressure. In the EVA, occurs the heat exchange between the solution and the secondary cooling fluid water, resulting in evaporation of the solution along the EVA, and on the other hand, cooling the secondary fluid coolant (water). Leaving the EVA as saturated vapor, the mixture flows to the ABS, where occurs a process of ammonia absorption with the weak ammonia-water solution coming from the GERA. In this process there is liberation of heat, characteristic of an exothermic reaction. This heat is rejected to the environment.

The weak solution that leaves the GERA to ABS, undergoes a throttling in RV3, causing pressure drop to a lowest level.

At the end of the absorption process in the AHEA, the solution in liquid state flows to the SP. This pump has two bias in the ARS: first, providing the movement of liquid within heat exchangers, making possible an increased heat and mass transfer, and secondly, to transporting the liquid solution of the low side pressure to the high side pressure, causing the internal liquid mixture in the GERA (Herold et al., 1996).

Modeling a SRA in transient regime is useful for analyzing the time response of system. In the scope of this work, the response time is the time period in which the temperature of the water in the evaporator achieves values in order to reduce the temperature of the medium should be controlled, e.g., the temperature into offices, intensive care units in hospitals, process fluids, etc. In SRA this time is very high compared to the vapor compression system, hence, know the behavior of the system in this initial time is important to seek constructive improvements of components and designing mechanisms of protection and control that benefits the reduction of response time.

2. MATHEMATICAL FORMULATION

For the development of transient model is taken as a basis SRA already shown in Fig. 1. Will be considered eight (8), where the balance equations are applied.

The system was modeled using material balance for the ammonia-water solution; concentration balance for the ammonia species; and energy balance around the system. For the calculation of heat flow, in the volumes where heat exchange is necessary, the Newton law of cooling will be applied, where convective heat transfer is important. The calculation of the average rate of heat removal will also be applied, in the heat exchanger cooling water secondary.

The balance equations of material, energy and concentration of ammonia species are shown in the Eqs. (1), (2) and (3).

$$\frac{dm_{vc}}{dt} = \sum_e \dot{m}_e - \sum_s \dot{m}_s \tag{1}$$

$$\frac{d(E)_{vc}}{dt} = \dot{Q}_{vc} - \dot{W}_{vc} + \sum_e \dot{m}_e . i_e - \sum_s \dot{m}_s . i_s \tag{2}$$

$$\frac{d(m_{vc}C_{vc})}{dt} = \sum_e \dot{m}_e . C_e - \sum_s \dot{m}_s . C_s \tag{3}$$

where m_{vc} is the initial mass in the control volume at time t initial, the subscript vc, signifies control volume, $\dot{m}_e$ and $\dot{m}_s$ are the mass flows that enter and leave the control volume, respectively. In Eq. (2), E is the energy stored inside the control volume and i_e and i_s are the enthalpy at the inlet and outlet of the control volumes, respectively. In Eq. (3), C_{vc} is the concentration of ammonia species in the control volume and C_e and C_s are the concentrations of ammonia species the inputs and outputs of the control volumes, respectively.

2.1 Closing Equations

To complement the set of equations, closing equations were necessary. Below some of these equations are shown. The sum of concentrations of ammonia and water:

$$C_{NH_3} + C_{H_2O} = 1 \tag{4}$$

For control volume of the secondary coolant, heat flow is determined using the following equation:

$$\dot{Q}_{vc} = \dot{m}_{H_2O} . c_{p.H_2O} (T_e - T_s) \tag{5}$$

where $\dot{m}_{H_2O}$ is the rate of flow of water circulating in the system, $\overline{c}_{p.H_2O}$ is the average specific heat of water, T_e is the water temperature at the inlet of the heat exchanger in the evaporator, and T_s is the water temperature at the outlet of the evaporator heat exchanger.

In the calculation of work rate done over the SP, the pumping process was considered as isentropic, isochoric and adiabatic, and the work rate being calculated by:

$$\dot{W}_{vc} = (p_{high} - p_{low}) \frac{v.\dot{m}}{\eta_{pum}} \tag{6}$$

where v is the specific volume of the liquid in the pump inlet, $\dot{m}$ is the mass flow rate, η_{pump} is the pump efficiency And p_{high} and p_{low} are, respectively, the pressures of high and low of the system. In the determination of pressure levels the work of Bourseau and Bugarel (1986) has been considered.

The heat flux through the control volume is given by:

$$Q_{vc} = U.A_T.\Delta T_m \tag{7}$$

where A_T is the total surface area of heat transfer and ΔT_m is an appropriate average temperature difference between the means involved.

Knowing the temperature of the wall of the GERA, $Tpde$, is an important data for the simulation of ARS. The equation that provides this knowledge is shown below:

$$\frac{dT_{pde}}{dt} = \frac{1}{m_{pde}c_{p_{pde}}} (Q_{gera} - Q_{sol,gera}) \tag{8}$$

where t is the time, m_{pde} s the mass of the wall of GERA, $c_{p_{pde}}$ is the specific heat at constant pressure the wall of the GERA, Q_{gera} is the heat flux of GERA and $Q_{sol,gera}$ is the flow of heat to the solution in the GERA. Heat flows: Q_{gera} e $Q_{sol,gera}$, arise from the convective heat transfer on the side of the burning of the fuel and in the solution inside GERA, respectively. The convective heat flow is calculated using Newton's law of cooling:

$$q"_{conv} = h(T_s - T_\infty) \tag{9}$$

where h is the coefficient of heat transfer, T_s is the surface temperature that is occurring the heat transfer and T_∞ is the temperature of the fluid, i.e., ambient temperature.

The total heat transfer is obtained by multiplying the heat flux cross-sectional area for the flow of heat, thus, the Eq. (12) take the following form:

$$Q_{conv} = h.A_T.(T_s - T_\infty) \tag{10}$$

The mass of the wall of GERA, m_{pde}, In Eq. (8), will be calculated by:

$$m_{pde} = \rho_{pde,gera}.VOL_{pde.gera} \tag{11}$$

The volume of the wall of GERA, is calculated considering the bottom of the GERA and the cylindrical wall to half the total height of the GERA, resulting in this equation:

$$VOL_{pde.gera} = \left[\frac{\pi.(D_{gera})^2}{4} + \pi.D_{gera}.L_{gera} \right].esp_{pde.gera} \tag{12}$$

where D_{gera} is the diameter of GERA, L_{gera} is the length of GERA and $esp_{pde.gera}$ is the wall thickness of the GERA.

In components as GERA and ABS, the height of a given fluid is essential for determining the mass flow rate of solution that will exit the control volume. In Fig. 2 is shown an schematic drawing of a cylinder positioned vertically, simulating a situation similar to what occurs in GERA and ABS.
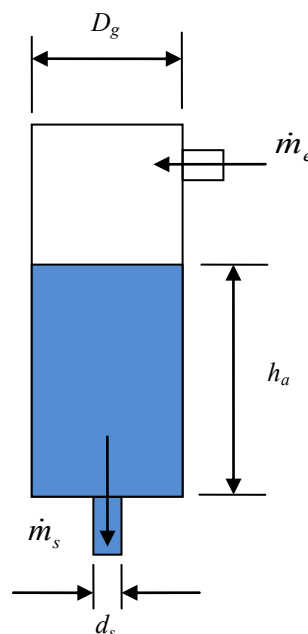

Figure 2. Diagram of vertical reservoir with fluid accumulation.

The amount of liquid that will exit the pipe diameter d_s, suffers the influence of gravity and the difference in pressure in the reservoir. The height of liquid, h_a, is determined from the volume of fluid in the reservoir:

$$VOL_l = m_l.v_l \tag{13}$$

where m_l, In Eq. (13), is the mass of fluid in the control volume and v_l is the specific volume of the liquid. VOL_l is given by the product of the cross sectional area of the cylinder, A_b, by the height h_a. So, the height of liquid in the reservoir is calculated by:

$$h_a = \frac{m_l.v_l}{A_b} \tag{14}$$

The mass flow coming out the bottom pipe, $\dot{m}_s$, is given by the product of the output speed, V_s, and the cross sectional area of the pipe.

$$\dot{m}_s = V_s.\left(\frac{\pi.d_s^2}{4}\right) \tag{15}$$

The exit velocity depends on the pressure difference present in the reservoir and the weight of the column of liquid in the cylinder:

$$V_s = \sqrt{\left(\frac{\Delta P}{\rho} + g.h_a\right).2} \tag{16}$$

where ρ is the density of the fluid, ΔP is the differential pressure in the cylinder and g is the acceleration of gravity. In the model adopted in this paper the pressure difference is considered null, so, the Eq. (16) will become simplified:

$$V_s = \sqrt{2.g.h_a} \tag{17}$$

3. NUMERICAL SIMULATION

The simplified SRA was divided into eight (8) and ten (10) points of states (Fig. 3). In each will be applied balance equations of mass, energy and concentration. Will be adopted following simplifying hypotheses, to facilitate the solution of the system of equations: 1) in the volumes where two phases are present, the liquid and vapor are in equilibrium thermodynamic; 2) the enthalpy on heat exchangers as COND and EVA will have a linear behavior in relation to its length; 3) the concentration of the two-phase flows in as: COND and EVA is considered constant; 4) the thermal capacity of the wall is disregarded, except in the GERA; 5) the solution is pumped at a constant volumetric flow rate at the BS; 6) the contributions of the kinetic and potential energies are disregarded in energy balance; 7) pressure drop in the were disregarded, except in reducing valves, e 8) there will be no heat exchange with the environment, except in the COND.

The model was implemented in EES® platform (F-Chart, 2013) that uses the Newton-Raphson method for the solution of the linear system.

4. RESULTS AND DISCUSSIONS

Besides taking into account the simplifying assumptions and the initial conditions shown in Tab. 1, some considerations were imposed for some parameters, with the aim of make feasible the simulation of ARS. In GERA, was considered that some steam out by Section 5 (Fig. 3), this must be in the saturated steam condition, so, its quality of steam is equals one. Was also adopted, which point 3, the mixture comes out in the state of saturated liquid, i.e., steam quality is zero. The temperatures at these points (3 and 5) were considered equal to saturation temperature, referring the pressure that is acting on the GERA in a given time step. The pressure difference between the output of point 3 and the generator was assumed to be zero.

In the the transient regime simulation, the dimensions of the components are important. In Tab. 2 the dimensions considered in the model are shown.

In the purpose of keeping pressure levels in acceptable values, two impositions were made in the simulation of ARS in the transient regime. The first: impose a maximum temperature to wall temperature of the GERA, not allowing it to be greater than 326.85 °C. The second: impose a maximum temperature for the temperature of the ammonia-water in the GERA, not allowing it to be greater than 121.85 °C. With this imposition the maximum temperature in the high

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pressure side will be fixed at 1.631×10^6 Pa and the minimum temperature be no longer than 1.63×10^5 Pa. In Fig. 4 one can check the graph with the high and low pressures with temperature control.
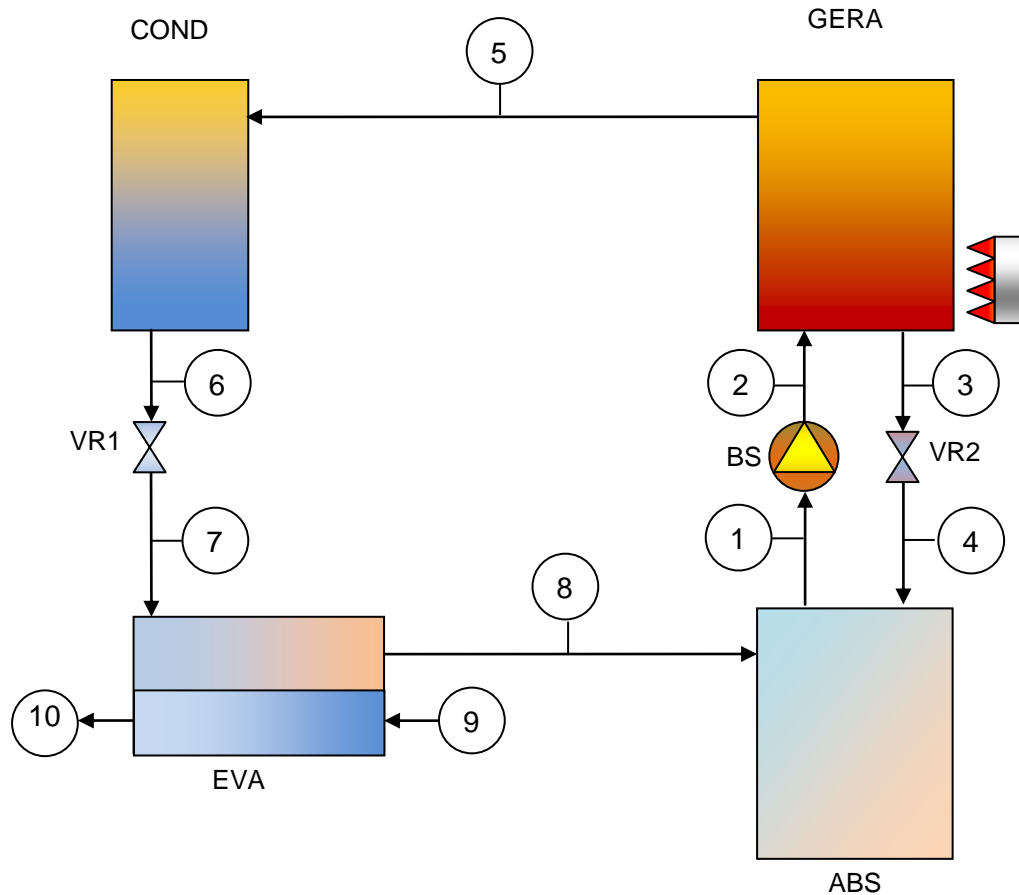

Figure 3. Simplified system for the simulation of ARS.

Table 1. Initial conditions for the transient simulation of ARS simplified.

Environmental Conditions	
Ambient temperature	35 °C
Atmospheric pressure	1.0130×10^5 Pa
Initial pressure in the generator	2.50×10^5 Pa
Burning System	
Temperature of combustion gases	326.85 °C
Ammonia-water Mixture	
Mass ammonia-water mixture	13.00 kg
Concentration of ammonia	33.00 %
System of Secondary Coolant	
Pressure centrifugal pump	2.45×10^5 Pa
Potency resistance of the boiler	10.00 kW
Water mass (fluid secondary)	29.91 kg
Water mass in the boiler	187.60 kg
Minimum temperature	7.00 °C
Maximum temperature	12.00 °C

Source: Kim and Park (2006) and Araújo (2010)

Table 2. Dimensions of components of the ARS simplified, to be used as initial data for the calculation of the volumes and areas necessary for the transient simulation.

Control Volume	Diameter (m)	Tube Length (m)
GERA	0.150	0.900
COND	0.016	18.000
EVA	0.018	30.000
ABS	0.100	0.800
SP	0.150	0.450

Source: Kim and Park (2006)

In Figure 5 shows all the points of states for the simulation of ARS simplified using the temperature control, with the total simulation time of 10 min. and 24 s (624 s).

Two been well defined temperature zones. A zone was positioned above of environmental temperature and and the second was positioned below ambient temperature. The points that are in the upper zone are: 3, 4 and 5, where 3 and 5 are output liquid of GERA and vapor outlet of GERA, respectively. Both are points of high pressure. The 4 point is located after the VR3, so, is a point of low pressure. The points of the are lower zone: 1, 2, 6, 7 and 8, where 1, 7 and 8 are Low pressure points, in which the 7 point is input EVA, 8 is the output of the EVA and 1 is output of the ABS. The temperature curve of the outlet of the condenser (point 6 the Fig. 5) has a sharp drop at the beginning of the simulation, reaching a minimum temperature of 9.60 °C, growing back to stabilize at 21.83 °C. These temperatures below environment temperature are due to the fixing of the coefficients global heat transfer.
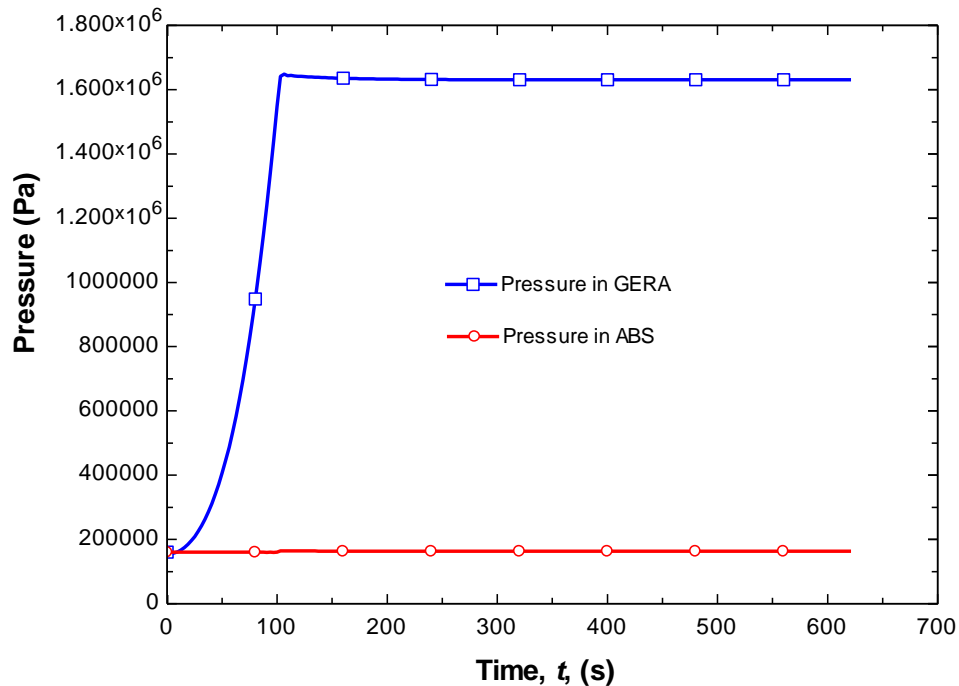

Figure 4. Pressure curves for ARS simplified.

Figure 6 shown are the temperature curves for inlet and outlet of water in the EVA, as well as, the temperature curve into the interior of EVA. Is observed that the temperature inside of EVA decreases rapidly and stabilizes at -20.00 °C, approximately. Water temperature at the entrance and outlet of EVA stays practically the same, throughout the simulation time. Increasing the inlet temperature of the water in EVA may be achieved by increasing the amount of heat supplied by the boiler.

Figure 7 shown are the curves of the masses entering and leaving the GERA. It is verified that the mass in GERA, remains constant at 12.05 kg, it caused by the constancy of the masses leaving the GERA.

In Table 3, shows the points of states to simulate the ARS simplified with temperature control. It is clearly observed two pressure levels: high and low pressure. The points 2, 3, 5 e 6 are on the high pressure side and points 1, 4, 7 and 8

are points of lower pressure. The lowest temperature of the system is in point 7 (inlet of EVA) and the highest are in 3 and 5 (outlet of fluid from GERA and GERA steam outlet, respectively).
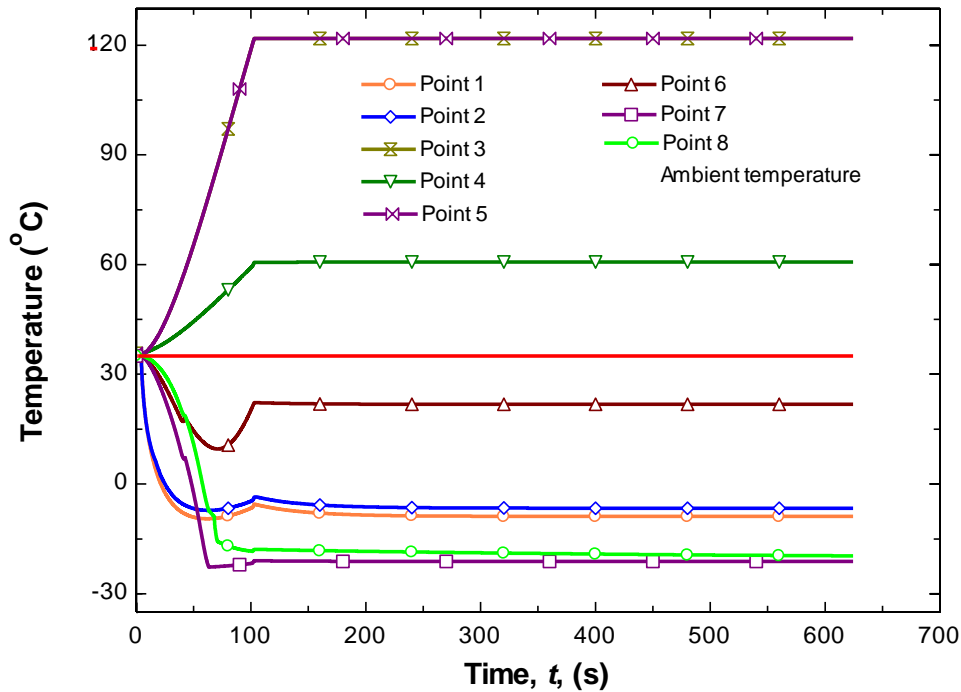

Figure 5. Temperature curves for points states of ARS.

The concentration of ammonia that flowing through the COND, VR2 and EVA was calculated as 90.53%, indicating a substantial presence of water, which indicates the need to use the rectifier to the purification of ammonia. The concentration of the liquid exiting the GERA showed a concentration the order of 31.61%, indicating that little mass of ammonia being released in GERA. The ammonia concentration in ABS has achieved a value of 65.12%, indicating a good absorption of ammonia from the EVA.
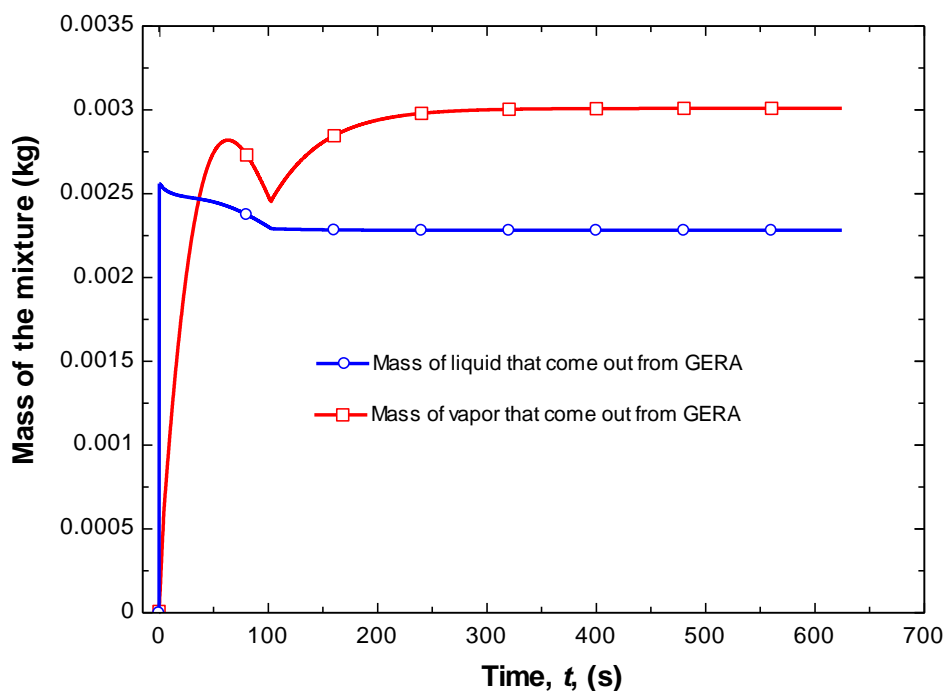
Figure 7. Curves of the masses of liquid and vapor that come out of GERA.

Table 3. Values of temperature, pressure, concentration, enthalpy and vapor quality for the simulation of ARS.

Point State	Temperature (°C)	Pressure (Pa)	Concentration of NH3 (%)	Enthalpy (kJ/kg)	Vapor Quality (%)
1	-8.87	1.630×10^5	65.12	-243.91	0.86
2	-6.62	1.631×10^6	65.12	-243.87	-0.10
3	121.90	1.631×10^6	31.61	341.52	0.00
4	60.69	1.630×10^5	31.61	341.52	15.67
5	121.90	1.631×10^6	90.53	1.62×10^3	100.00
6	21.78	1.631×10^6	90.53	33.69	-0.10
7	-21.18	1.630×10^5	90.53	33.69	14.97
8	-19.65	1.630×10^5	90.53	420.74	43.33

In analyzing the quality of steam along the ARS, It can be observed that the two points on the conditions of saturated liquid (point 3: vapor quality = 0,00 %) and saturated vapor (point 5: vapor quality = 100,00 %) were imposed. After passage of the solution by VR3, point 4, vapor quality changes from saturated liquid to humid vapor quality of 15.67 %. In point 1, outlet of ABS, the quality is 0.86% and enter in fluid reservoir the pump and then be pumped to the point 2, quality changes from humid vapor for subcooled liquid (point 2: vapor quality = -0,10). In COND, the state of vapor at point of entry is the saturated vapor (point 5: vapor quality = 100,00 %) changing to compressed liquid at the outlet (point 6: quality = -0.10%). At the EVA inlet, the solution comes as humid vapor, with vapor quality 14.97% (point) and also exit as humid vapor, with quality of 43.33% (point 8). The behavior of the curve quality to the points of inlet and outlet COND and EVA, can be seen in Figs. (8) and (9) respectively.
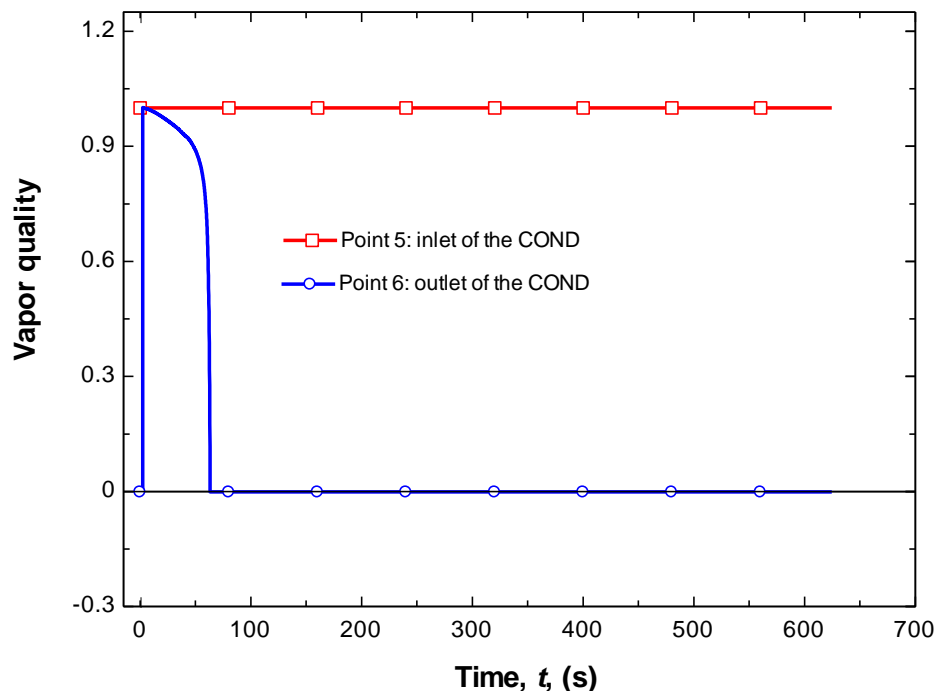

Figure 8. Vapor quality curves for points of inlet and outlet of COND.
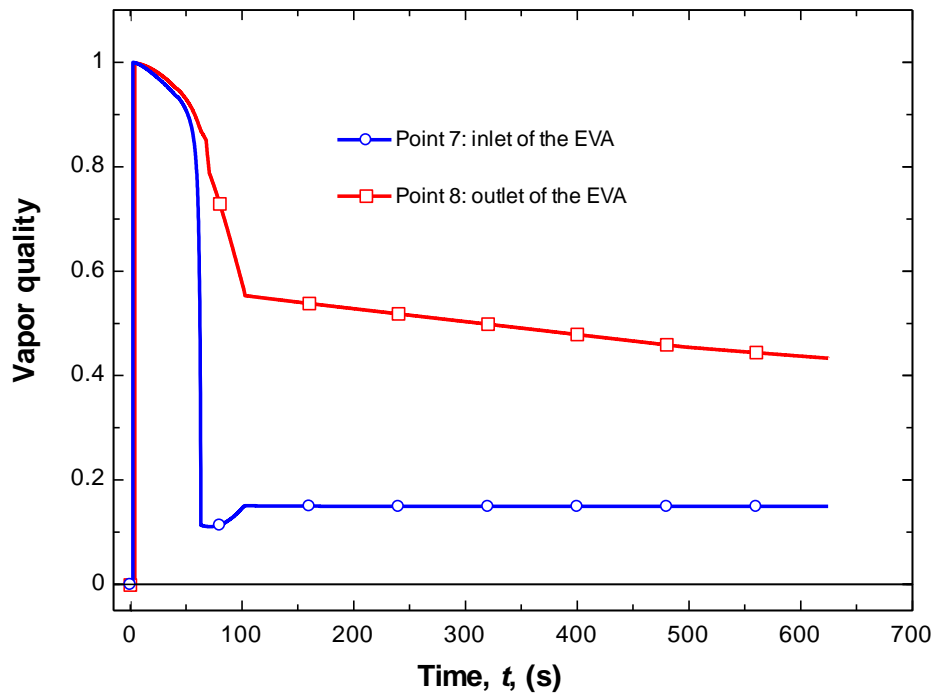
Figure 9. Vapor quality curves for points of inlet and outlet of EVA.

The instantaneous coefficient of performance (COPI) can be seen in Fig. 10. o coefficient of performance (COP) increases at the beginning of the simulation, peaking at 0.1722, then decreases to 0.06801. The COP for the system in the present study was calculated as 0.5672. For this value, the ARS simplified presented a low efficiency, this indicates that the components of internal heat recovery shall be incorporated to improve the performance of the ARS.
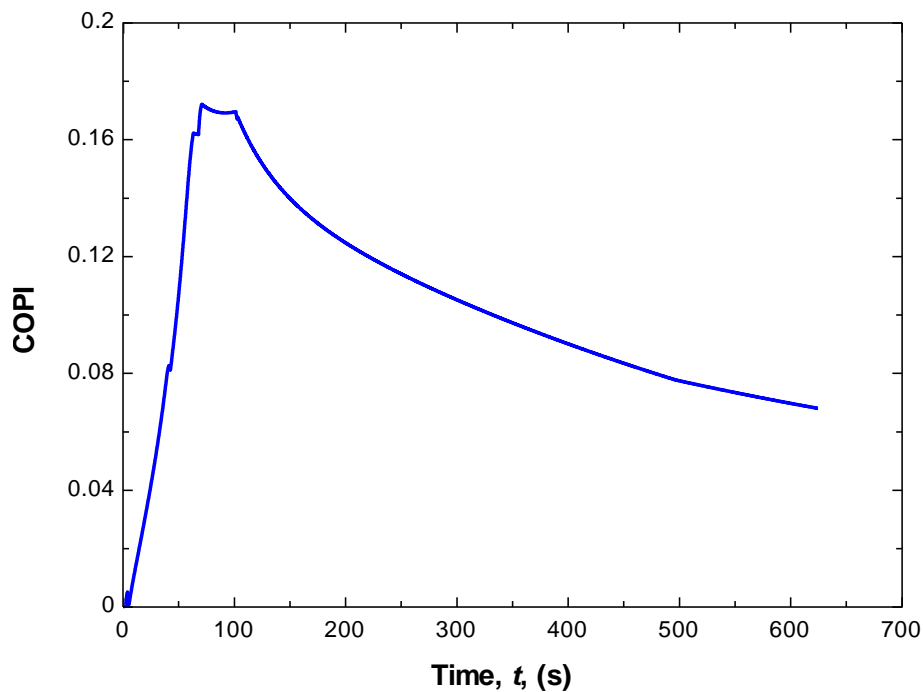
Figure 10. Graph of instantaneous coefficient of performance for the simulation of ARS simplified.

5. SUMMARY

The model was developed on the EES® platform that due to its large library of thermodynamic properties, made possible a more simplified implementation.

With all the simplifications imposed and with initial conditions applied, is obtained a data set that analyzed, results in the following conclusions:

- in the transient simulation, behavior inside the control volume is of fundamental importance, not only the pressure should be monitored, but also temperature, ammonia concentration and mass;
- two components are important for the proper functioning of the system: The GERA and ABS. The GERA shall always supply a steam solution of ammonia-water, with high ammonia concentration, to ensure the cooling of the secondary coolant in the EVA. The ABS shall always maintain a level of solution inside it to ensure solution within the BS;
- the concentration of ammonia in the COND and EVA stabilized around 90.53%, showing a quantity of 9.45% more water than desired;
- a concentração de amônia do líquido que sai do GERA ficou na ordem de 31,61 % e no ABS a concentração encontrada foi de 65,12 %;
- a qualidade na saída do EVA ficou em 43,33 %, indicando que uma grande quantidade de líquido está saindo do EVA sem ser evaporado, prejudicando a eficiência do sistema.

Despite the transient simulation have been in a SARS simplified, it was proved that the transient simulation for complex systems is possible and should be encouraged. The EES® The EES showed a tool for easy programming and does not require high knowledge of programming language, besides presenting a library of functions useful to those working in the field of thermodynamics, heat transfer and fluid mechanics.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE