Investigation on the possibility of substituting compression cooling cycle with a solar absorption cooling cycle in tropical regions of Iran

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ABSTRACT. *In this paper, cavity flow is simulated numerically. Forced convection in different Reynolds number between 100 and 5000 is simulated. Different and complex thermal boundary conditions are applied and various parameters are calculated numerically. Up wall and down walls are in constant temperature and left and right walls are thermal insulation in the first thermal boundary condition. The Left and the down walls are in constant temperature and temperature of the up and the right walls changes linearly in the second thermal boundary condition. For third thermal boundary condition, the left and the down walls are in constant temperature and temperature of the up and the right walls changes sinusoidally. For this purpose, a code is written in the FORTRAN software. Streamlines, isotherms, velocity and temperature in centerlines of cavity, Nusselt number and mean Nusselt number are obtained and shown in different figures and one table. Grid independence is surveyed and some obtained results are validated with other researchers work. In these simulations, Prandtl number is considered to be 0.71 because of air's Prandtl number. For time discretization, a fifth-order Runge-Kutta is used and for convective fluxes, averaging scheme with forth-order damping term is applied. To calculate second order derivations, secondary cells are used by aid of the Green theorem.*

RÉSUMÉ. *Dans cet article, l'écoulement dans la cavité est simulé numériquement. La convection forcée dans différents nombres de Reynolds entre 100 et 5000 est simulée. Des conditions aux limites thermiques différentes et complexes sont appliquées et divers paramètres sont calculés numériquement. Les murs du haut et du bas sont soumis à température constante et les murs de gauche et de droite constituent une isolation thermique dans la première condition aux limites thermiques. Les murs de gauche et du bas sont soumis à température constante et celle des murs du haut et de droite changent linéairement dans la deuxième condition aux limites thermiques. Pour la troisième condition aux limites thermiques, les murs de gauche et du bas sont soumis à température constante et la* *température de ceux du haut et de droite changent de façon sinusoïdale. Dans ce but, un code est écrit dans le logiciel FORTRAN. Les lignes de courant, les isothermes, la vitesse et la température dans les lignes centrales de la cavité, le nombre de Nusselt et le nombre moyen de nombre Nusselt sont obtenus et représentés par différentes figures dans un tableau. L'indépendance de la grille est étudiée et certains résultats obtenus sont validés par d'autres recherches. Dans ces simulations, le nombre de Prandtl est considéré comme égal à 0,71 en raison du nombre de Prandtl de l'air. Pour la discrétisation dans le temps, les méthodes de Runge-Kutta d'ordre cinq est utilisé pour les flux convectifs, un schéma de calcul de moyenne avec un terme d'amortissement à l'ordre quatre est appliqué. Pour calculer les dérivations à l'ordre deux, les cellules secondaires sont utilisées à l'aide du théorème de Green.*

KEYWORDS: *cavity flow, forced convection, reynolds number, complex boundary condition, nusselt number.*

MOTS-CLÉS: *écoulement dans la cavité, convection forcée, nombre de reynolds, condition aux limites complexes, nombre de nusselt.*

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1. Introduction

Proper cooling is one of the main concerns of tropical regions of Iran. In some of these areas, relative humidity is high and there is no possibility of using evaporative cooling. Vapor-compression refrigeration system (VCRS) and absorption cooling (absorption chiller) are some of the methods used for cooling. A compressor is used to increase pressure and temperature of working fluid during compression cooling cycle while in an absorption cooling cycle first boilers exhausted vapor dissolves in absorbing liquid Then the pressure of the liquid from the absorber increases with the pump and in the heat exchanger and the generator, the temperature rises and the gas with high temperature and pressure goes out of the liquid and enters the condenser. Considering that specific volume of sub-cooled liquid is much lower than superheat vapor and consumed work for increasing pressure is calculated by the relation =*fvdp*. So that the work of the compressor to increase the pressure of a gas is far more than the work of the pump to increase the pressure of a liquid. Therefore, the work and electrical energy consumed in compression cooling cycles are far more than absorption cooling cycles. Absorption cooling cycles require heat in the generator. While compression cooling cycles do not require such energy. The thermal energy required for absorption cooling cycles can be supplied from fossil fuels, in which case these cycles will not differ much in terms of energy consumption and exergy destruction with compression cycles. If cooling cycle's heat could be supplied from energy-free sources such as solar energy, the absorption cooling cycle will be superior to the compression cooling cycle.

Lu *et al.*, (2013) established a novel kind of expanders. This expander was applied to refrigeration systems. They determined experimentally the refrigeration performance of a compressed air refrigeration system which is based on a single screw expander with 175 mm diameter rotor. Wang *et al.*, (2006) offered a novel compressed air energy storage refrigeration system for electrical power load shifting application. It is a combination of a gas cooling cycle and a vapor compression cooling cycle. Elsafty and Daini (2002) presented a study of the general cost linked with single- and double-effect vapor absorption and vapor compression air-conditioning systems. The cost examination considered the initial costs and the operating costs of each of the three systems. Sozen *et al.,* (2004). proposed a solar aided cooling to be a substitute for the usual electrical driven units. The highest benefits of solar aided cooling systems concern the lessening of top loads for electricity utilities, the use of zero ozone depletion impact refrigerants, the reduced primary energy consumption and decreased global warming impact. Zhai *et al.,* (2007) coveyed the solar energy system for Shanghai. Shanghai has subtropical monsoonal climate with the mean annual temperature of 17.6 °C, and receives annual total radiation above 4470 MJ/m^2 with approximately 2000 h of sunshine. A solar energy system capable of heating, cooling, natural ventilation and hot water supply has been made in this work. Adibi *et al.,* (2017). studied the effect of the intercooler on the network and efficiency of Brayton cycle. In this investigation, different states such as ideal Brayton cycle with intercooler and with or without regenerator and also real BCs are considered.

Brown *et al.,* (1997) did a research on solar energy. Numerous uses of solar energy have confirmed viable in the energy marketplace, due to economical technology and economic performance. One sample is the parabolic trough solar collectors, which use focused solar energy to maximize efficiency and reduce material use in construction. Henkel (2005) discussed novel solar thermal collectors that use non-imaging optics, numerous projects that use the new collectors, and new solar thermal building applications for the very near future.

Mittal *et al.,* (2006) simulated a solar powered absorption cooling cycle with an absorption working pair of lithium bromide and water. The system contains a flat plate solar collector, a lithium bromide water absorption chiller, an auxiliary energy source and a hot water storage tank. They modelled a solar absorption cooling system by a flat plate collector in computer software for all potential climatic conditions of Bahal, India. Their results displayed that for each ton of refrigeration, a minimum collector area of 26.02 m^2 with an optimum water storage tank volume ranging from 1000 to 1500 L is needed, so that the system can work only on solar energy for ~7h a day. Burns *et al.,* (2007) displayed the results of a preliminary calculation of the technical and economic possibility of added solar thermal absorption cooling cycle for small commercial and institutional buildings in the Southwestern United States. Their results showed that solar thermal cooling cycles are possible in areas with a union of high solar insolation, high cooling request, and high electric charges, achieving payback of less than 8 years in typical five-story buildings. Also their results showed that in smaller buildings, solar thermal absorption cooling system life-cycle costs are also encouraging in comparison to conventional cooling systems.

Tsekouras *et al.* (2016) proposed a small-scale solar thermal system for cooling an office building in Athens, Greece in their work. They reported the data and displayed the experimental results from the first complete summer period. Based on their results the daily electrical coefficient of performance (COP) of the absorption chiller was 48.6 and the electrical COP of the solar system was 10.9. Blackman & Bales (2015) proposed a new absorption system. This system contains a fully encapsulated sorption tube comprising hygroscopic salt sorbent and water as a refrigerant, sealed under vacuum, and within which there are no moving parts. The absorption system has two chief parts, one that alternately functions as an absorber or generator and other that alternates between the roles of evaporator and condenser. Adibi applied renewable energy to cooling purpose in the Middle East. The cooling load is calculated for major cities of the Middle East. An ammonia absorption refrigeration cycle (AARC) is used for cooling purpose. Solar energy is considered as the high temperature source.

Fluctuations in the price of fossil fuels in recent years, as consequence fluctuations in the price of electrical energy obtained by fossil fuels, as well as the devastating effects that fossil fuels have on nature, has led to countries switching to alternative energy sources. Solar energy is an alternative source which is free and available for everyone. Iran, which is located of northern 25°-42° and eastern 44°-62° receives far more solar energy than global average. In Iran, 280 sunny days have been reported. Different cities of Iran enjoy proper solar energy Average of solar radiation ranging (ASR) for different cities of the country is higher than its global average. For example, cities of Bandar Abbas, Mashhad, Tehran have ASR 5.57, 4.74 and 4.58 ($kWh/m^2/day$). Due to the high solar energy received in Iran, the use of solar absorption cooling systems can be a good alternative to condensing cooling systems. Benefits of using adsorption systems are to reduce greenhouse effect, reduce air pollution, reduce power consumption and reduce energy costs. Cities like Bandar Abbas (with a geographical position of 27 ° north and 56 ° east), which include hot and humid summers with a dry temperature of $T_{db}=41^0C$, a wet temperature of $T_{wb}=32^0C$ and a daily temperature difference of $T_{DR}=10^0C$, generally use compression cooling systems in purpose of cooling.

Goldstein et al. simulated a two-storey building in the hot and dry climate. This building is cooled by absorption cooling system. Burst *et al.* (2016) worked on solar panels. Their results show that solar cells can fabricated with open-circuit voltage greater than 1 V.

Boustani and Lavasani (2016) investigated exergy efficiency of solar panel. They used generic algorithm.

In this study, the efficiency of solar absorption cooling systems as an alternative to compression air cooling systems in the tropical regions of Iran has been investigated.

2. Governing equation of compression and absorption cooling cycle

Compression cooling cycles and absorption cooling cycles are shown in Figures 1 and 2.

Cities within the tropical regions of Iran such as Abadan, Ahvaz and Dezful are experiencing temperatures above 45°C in the summer. Sometimes even temperatures above 50°C can occur in these cities. On the other hand, the comfort temperature can be determined between 15 to 25°C. In the cooling cycle condenser, heat is released to the outer environment. Depending on the ambient temperature, the internal temperature of the fluid in the condenser should be above 70°C, in order to have a reasonable temperature difference. Also, to get heat from a cool environment (such as an apartment, school, office building, etc.), the inside evaporative temperature should be about 20 degrees lower than the ambient temperature. Consequently, the temperature of the fluid in the evaporator should be about 0°C. According to the conditions mentioned above, a compression cooling cycle was simulated in EES software. The pressure- enthalpy (P-h) diagram of this cycle is illustrated in the ideal and non-ideal manner with the working fluid R134a in Figures 3 and 4.

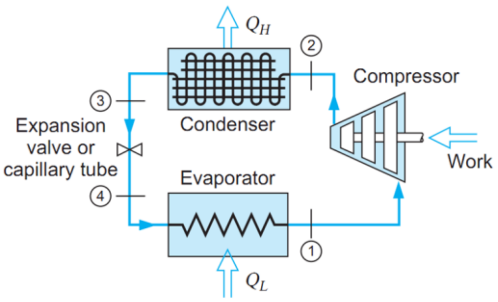

Figure 1. Compression cooling cycle (Borgnakke & Sonntag, 2015)

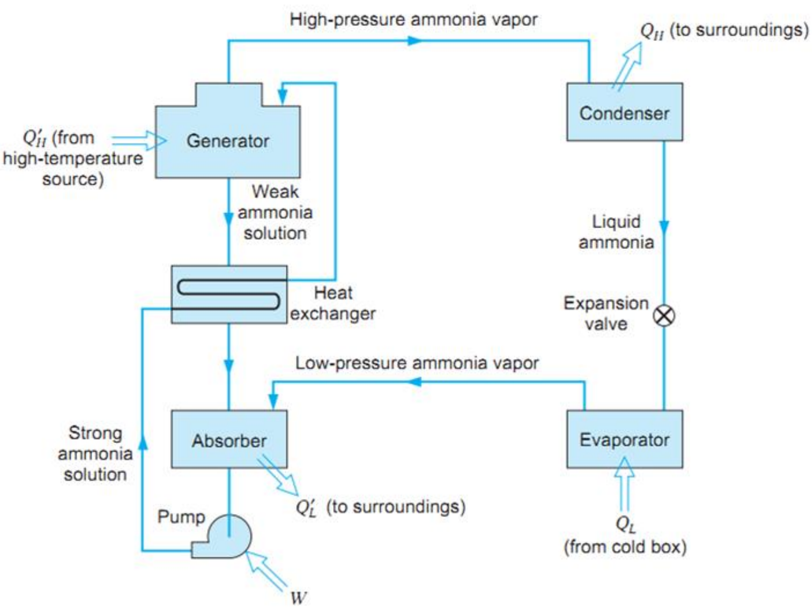

Figure 2. Absorption cooling cycle

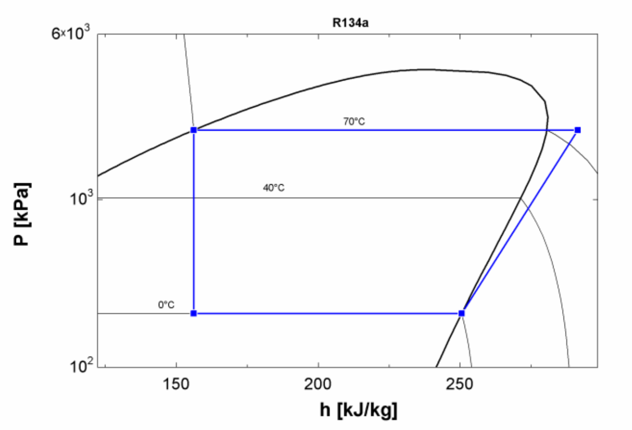

Figure 3. P-h Diagram for ideal compression cooling cycle with R134a as working fluid

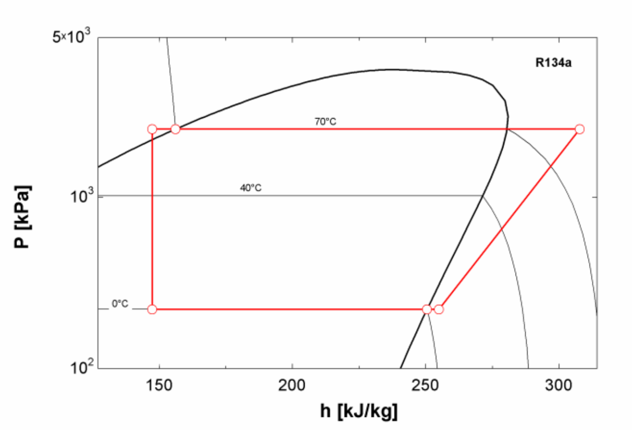

Figure 4. P-h Diagram for non-ideal compression cooling cycle with R134a as working fluid

In simulations, the pressure inside the condenser and evaporator is assumed to be constant. It is also assumed that the enthalpy of the inlet and outlet of the expansion valve is constant. Increasing the pressure and temperature is isentropic in the compressor, the inlet of the compressor is the saturated vapor and the inlet of the expansion valve is saturated liquid in the ideal process. In actual process, efficiency of compressor is below 100%, the inlet of compressor is superheat vapor and the inlet of expansion valve is saturated liquid. The energy consumption of the compressor, the evaporator generated cooling and the coefficient of operation of the cycle are important parameters of compression cooling cycle. To simulate the cycle, the temperature, enthalpy, pressure and entropy of the different points were determined using thermodynamic tables. Thermodynamics relationships have been used to determine the compressor work, evaporator cooling and coefficient of cycle performance. The following equation has been used to determine cycles work consumption.

$$w_c = h_2 - h_1 \tag{1}$$

The following equation has been used to calculate the evaporator generated cooling.

$$q_l = h_1 - h_4 \tag{2}$$

The coefficient of the compression cooling cycle is obtained from the following equation

$$COP = \frac{q_l}{w_c} \tag{3}$$

The coefficient of the absorption cooling cycle is obtained from the following equation.

$$COP = \frac{q_l}{w_p + q_{gen}} \tag{4}$$

In relation (4), the pump's work consumption will be negligible compared to the heat given to the cycle in the generator, and the coefficient can be defined as follow.

$$COP = \frac{q_l}{q_{gen}} \tag{5}$$

In actual mode, the compressor output is determined from the following equation

$$\eta = \frac{w_{cs}}{w_{ca}} = \frac{Ideal\ work}{Actual\ work} \tag{6}$$

3. Results and discussion

For condensation cooling cycles, a variety of fluids are used. Some of these cycles, such as the cycle using air as working fluid, work in single-phase mode. However, most compression cooling cycles work in two-phase mode, which we have investigated in this study. R12, R22 and R134a are the most commonly used operating fluids in these cycles. Due to the fact that the R12 and R22 fluids cause ozone depletion, in this paper, the R134a is considered as working fluid of compression cooling cycle. Assuming different compressor outputs, compression cooling cycles were simulated in EES software. The results are shown in Table 1 and Figure 5.

Table 1. obtained results from EES software

Compressor efficiency	85	70	55
Evaporator outlet temperature (^0C)	0	0	0
Condensing input temperature (^0C)	82.62	90.61	103.6
Inlet expansion valve temperature (^0C)	70	70	70
Quality of expansion valve output (%)	52.5	52.5	52.5
Pressure inside evaporator (kPa)	293	293	293
Pressure inside condenser (kPa)	2118	2118	2118
Consumed work(kJ/kg)	48.18	58.51	74.46
Generated cool(kJ/kg)	94.33	94.33	94.33
Coefficient of performance	1.958	1.612	1.267

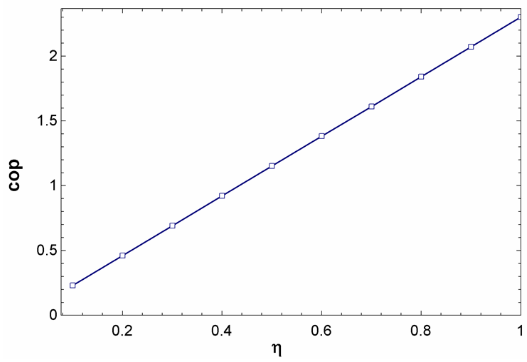

Figure 5. The COP varies related to the Compressor efficiency

The cooling load of a 4-story building with an area of 300 m2 in Bandar Abbas has been calculated in another study. The calculated cooling load was about 50 kW. According to Table (1), If a VCRS with an R134a working fluid and 70% efficiency compressor is used to cool this building, 30 kW of electrical energy is required. If, instead of using the compression cooling cycle, the absorption cooling cycle with a coefficient of operation of about 1, according to equation (5), 50 kW of heat in the generator should be given to the fluid to be absorbed into the cooling cycle. Solar panels can be used to provide the required heat in the absorption cooling cycle. The heat calculated from these solar panels is obtained from the following equation.

$$Q_g = G * A * \eta_p \tag{7}$$

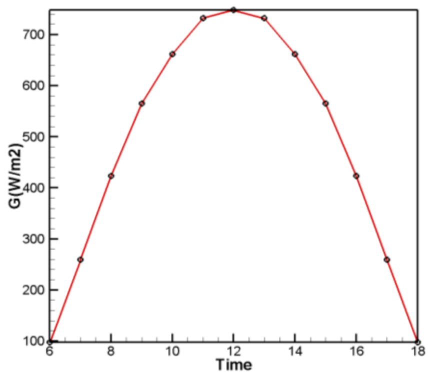

Figure 6. The heat received from the sun at latitude 30 on 11 June throughout the day

The average amount of heat received during the day varies over the warm months of the year. For example, according to information, the heat received from the sun throughout the day on 11 June in latitude 30, where the tropical cities of Iran are located almost on this latitude, is shown in Figure 6.

The heat received varies throughout the day and during the warm months of the year. As well, the cooling load of a building varies throughout the day and during the warm months of the year. However, it is clear that by approaching the warmer months such as July, as well as approaching noon, both the cooling load and the heat coming from the sun rises. Having said that, the peak of cooling load and receiving heat from the sun happens simultaneously, which are 50 kW and 750W/m^2 respectively. Consequently, to provide the required heat in the generator, the absorption cooling cycle in the case study building will require about 70 m^2 of solar panels. Consequently, the electrical energy consumption can be dramatically reduced by equipping the building with an absorption cooling system using 70 m^2 solar panel compared to using a compression cooling system such as VCRS. Economically, the price of electrical energy and the cost of the equipment needed for the solar-absorption cooling system should be taken into consideration. The average price of electrical energy is 15 cents per kilowatt hour. A square meter of the solar panel is about $150. The solar panel's initial cost will be about $10,000. Given that the other initial costs are insignificant compared to the cost of solar panels, there is no need to calculate the rest. Replacing the solar cooling system reduces current costs by reducing electric power consumption. The cooling load of this building at its peak is 50 kilowatts, resulting in an average cooling load of 5 kilowatts per year and a total cooling load of one year in the building of about 50 megawatts. The cost of electric energy consumed by this building will be about $5,000 each year. As a result, the length of the return period will be about two years. In all of these calculations, global prices have been considered. Although this research has explored a specific building in Bandar Abbas, it can be extended to similar buildings in tropical cities and even cold climates in Iran. Despite the fact that in the cold cities of Iran, the amount of solar energy received is lower than the tropical cities of Iran, the cooling load of the buildings in these cities is less than the cooling load of the buildings of tropical cities. In this way, without the use of significant electrical energy, it is possible to create a very pleasant air in the tropical cities of Iran at very low operating costs during the warm months of the year.

4. Conclusion

In this paper, a compression cooling cycle was simulated in EES for ideal and non-ideal conditions. The working fluid was R134a, and the purpose of this cycle was to create cooling in the tropical regions of Iran. A four-story building with a surface area of 300 m^2 in Bandar Abbas was studied, cooling load of 50 kW was calculated. According to the simulation of compression cooling cycle, the amount of compressor work was used to cool this residential building determined 30 kW. The compression cooling cycle was then replaced with a solar absorption cooling cycle. The results illustrated that the use of 70 square meters of solar panels could provide the required heat of absorption chiller to generate the desired cooling. The use of solar energy reduces the consumption of electric energy, reduces the cost of cooling system operation, reduces greenhouse gas emissions and reduces environmental pollution. Replacing the solar absorption cooling system with the compression cooling system could gain many positive consequences.

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Nomenclature

a	Actual	p	Pressure
c	Compressor	q	Heat transfer
cop	Coefficient of performance	s	Isentropic
gen	Generator	v	Volume
h	Enthalpy	W	Work
l	Low temperature heat source		