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Annual Thermal Performance Assessment for an Economized Vapor Injection System in Hot Climate

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ABSTRACT

Improving the energy consumption efficiency in air conditioning (AC) systems has been increasingly necessary due to the sustainability vision of Kuwait 2035. The refrigerant vapor injection (VI) technique has been proven to significantly enhance heating cycles as well as cooling systems. The VI technique lowered compressor discharge temperature, improved cooling capacity, and therefore enhanced system's coefficient of performance (COP). In this study, numerous data have been sampled from the literature and analyzed to correlate the VI technique's cooling COP with operating conditions at hot climate. The data were sampled from previous experimental works at high ambient temperatures ranging from 20°C to 52°C. Three empirical formulas, each with unique correlations and temperature parameters, were developed to predict the COP of the VI cooling cycles with only a maximum mean absolute error of 3.81%. The results showed that the VI technique enhanced the cooling COP up to 34% during July (hottest month in Kuwait) when compared with the conventional cooling cycle. More experimental studies were recommended to thoroughly evaluate the cooling impact of the VI system when operating in the Gulf Cooperation Council (GCC) countries.

1. INTRODUCTION

The global demand for air conditioners is expected to triple by 2050, while the use of air conditioning (AC) units and electric fans to cool building accounts for a fifth of total electricity used in buildings worldwide (IEA, 2018). The International Energy Agency (IEA) (IEA, 2018) reported that improving cooling efficiency can cut the energy growth demand from AC in half through mandatory energy performance standard . Kuwait sustainability vision 2035 mandates the innovation in the energy sector to reduce the demand for energy (UNDP, 2019). Kuwait's energy consumption in buildings contributes about 40% of its total demand, in which about 70% of that energy is consumed by AC systems (UNDP, 2019). Therefore, energy efficient solutions need to be adopted and implemented to reduce and control the electrical requirements as well as the environmental concerns. The operation of cooling air in an enclosed space involves a vapor compression cycle (VCC) operation. A typical VCC setup is usually comprised of a compressor, a condenser, an expansion valve, and an evaporator. Within the VCC system a specific type of refrigerant circulates through the system carrying and offloading heat to cool the air being supplied to the enclosed space. While the VCC system proves to be effective at comfortable ambient temperatures (*i.e.,* 35°C), it starts to lose efficiency at high and extreme hot ambient temperatures (*i.e.,* 46°C to 52°C) (Bahman et al., 2018; Tello-Oquendo et al., 2016). To counteract the issue of losing efficiency, the vapor injection (VI) technique is introduced to the system to increase cooling system's performance (D. Lee et al., 2015). The VI approach usually introduces additional economizer (heat exchanger) or flash tank, and an expansion valve to the typical VCC system to further subcool the refrigerant and increase the cooling capacity. The main idea of VI technique is injecting part the refrigerant that's passing through the economizer into the compressor to absorb the heat generated during the compression stage and reduce the power consumption, and therefore enhances the system coefficient of performance (COP). Fig. 1a presents the standard cooling cycle setup with VI configuration. The economizer that could be either a heat exchanger or flash tank that recycles energy produced with the system and leverages environmental temperature differences to achieve higher efficiency. A flash tank is used instead or with a heat exchanger and acts as a refrigerant separator where the refrigerant vapor is injected to the compressor while the refrigerant liquid expands to the evaporator. However, the internal heat exchanger is more favorable to control the refrigerant injection state due the larger range of operation. The VI system resulted in an increased subcooling degree as opposed to the conventional (baseline) VCC system as shown in Fig. 1b. The VI method increased the cooling capacity due to the increase of enthalpy of vaporization across the evaporator and improved the heat recovery during the compression process (D. Lee et al., 2015). To this end, the use of VI method at an intermediate state of the compression process demonstrated to reduce the compressor discharge temperature and improved the system cooling capacity using an economizer, and therefore enhance the system's cooling COP.

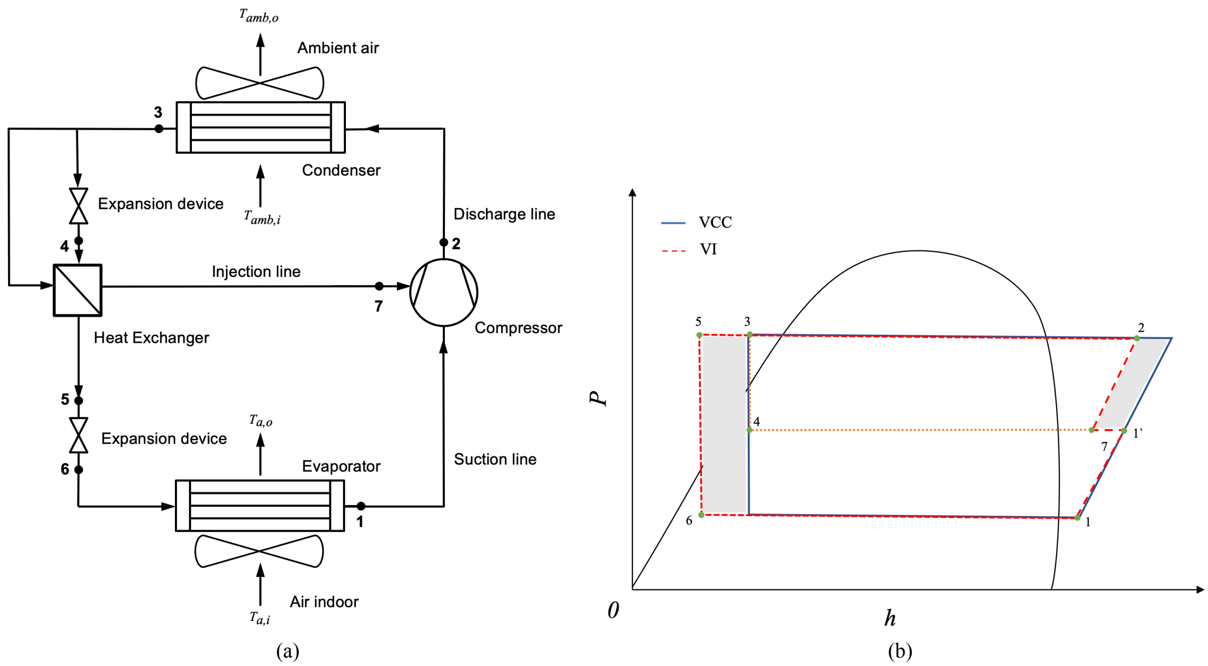

Figure 1: (a) Schematic of typical cooling cycle setup with vapor injection (VI) configuration, and the corresponding (b) pressure-enthalpy diagram of the VI system compared to the conventional vapor compression cycle (VCC) system.

To the best of the authors' knowledge, an annual thermal analysis for the VI system has not been assessed yet in hot climate conditions, specifically at high ambient temperatures of up to 52°C. Weather data for Kuwait were sampled and analyzed as a case study to produce evidence that the VI approach is applicable in harsh hot climates. Through literature, experimental data for VI cooling systems operating at high ambient temperatures were collected to evaluate the effect of VI technique on the COP of a cooling system. Correlations for the cooling COP to predict the annual VI cooling performance were developed. Using a common thermodynamics software, the experimental data form the literature were analyzed and correlated to find the best fit between the influence parameters. In the end, the VI system performance was compared with the conventional cooling system to evaluate the implementation of the VI technology for Kuwait case.

2. APPROACH & METHODS

2.1 Weather data collection

Kuwait and Gulf Cooperation Council (GCC) countries are the hottest and driest countries in the world and would benefit from the implementation of the VI technique into the AC system. To further study the benefit VI has in extreme hot climates, whether data for Kuwait was gathered and recorded because the ambient temperature and humidity levels directly affects AC system's COP (Shuxue et al., 2013; Xu et al., 2013). The weather data was collected from Kuwait Meteorological Center (KMC) (KMC, 2020 (accessed January 21, 2022)) and National Oceanic and Atmospheric Administration (NOAA) (NOAA, 2017 (accessed January 21, 2022)), respectively, and reported in Abdal (2022).

2.2 Performance data collection

The parameters and conditions that affected an AC system's COP were collected from numerous studies and summarized in Abdal (2022) to derive an empirical formula that can accurately predict a VI system's COP (Bahman et al., 2018; Bahman, 2018; Tello-Oquendo et al., 2016; H. Lee et al., 2013; D. Lee et al., 2015; H. Cho et al., 2009; I. Y. Cho et al., 2016; Chung et al., 2018; Siddharth et al., 2004; Kang et al., 2008; Kim, Song, et al., 2018; Kim, Jeon, et al., 2018; Luo et al., 2020; Roh et al., 2014; Shuxue et al., 2013; B. Wang et al., 2009; X. Wang et al., 2009; Xu et al., 2013; Yang et al., 2021; Zhang et al., 2016; Fan et al., 2020). Temperature related data as well as cooling capacity data was gathered from literature that resembles the main factors that affect a system's COP. The data were collected from studies that examined residential AC units within an average range of 2 to 8 RT. Since the focus of study is the cooling process at high ambient temperatures, data collected for ambient temperatures ranged from 25°C and above. The steady state cooling process was considered without including the transient state process to avoid further complexity. The refrigerant type was included in calculating the baseline system's COP without VI technique. Cooling systems with one compression stage with built-in injection port were the focus of study, yet two experiments that included two compression stages with injection were considered as well.

2.3 Baseline VCC system modeling

In order to compare the COP of the VI system with a system without VI, the basic VCC cooling cycle was modeled. To obtain precise results, the simulation model used exact parameters (ambient, condensation, and evaporation temperatures) from the literature. The same conditions were duplicated to show the effect the VI technique had on the cooling cycle.

2.3.1 VCC thermodynamic analysis

The basic refrigeration cycle was modeled using thermodynamic assumptions presented in Abdal (2022). Each subscript indicates one of the four stages of the basic cooling cycle. The states are shown in Fig. 1 without considering the addition of the heat exchanger or the second expansion valve. Subscript 4 will be assigned instead of 6 as shown in the figure because states 4 and 5 in Fig. 1 will be ignored since the second EXV will be closed so that no refrigerant mass is injected. The engineering equation solver (EES) software (Klein & Alvarado, 2019) was used to solve the set of equations to obtain the properties of the refrigerants.

The mass flow rate of the refrigerant in the VCC cycle is derived from the cooling capacity as shown in Eq. (1). The compressor's power consumption and the COP of the basic cycle are expressed as in Eqs. (2) and (3), respectively (Bahman et al., 2014).

$$\dot{m} = \frac{\dot{Q}_{evap}}{h_1 - h_4} \tag{1}$$

$$\dot{W} = \dot{m}\left(h_{2a} - h_1\right) \tag{2}$$

$$\text{COP}_{\text{VCC}} = \frac{\dot{Q}_{evap}}{\dot{W}} \tag{3}$$

In the simulation, the evaporation temperature was calculated using $T_{evap} = T_L - T_{sh} - T_{pinch}$ and the condensation temperature was calculated as $T_{cond} = T_H + T_{sc} + T_{pinch}$. The assumptions used to design a typical residential air-conditioning unit operating at Kuwait weather condition as following (Bahman et al., 2014; Barghash et al., 2021):

- Cooling capacity of AC unit varied from 2 to 8 RT ($\dot{Q}_{evap}$ = 7.03 to 28.13 kW) depend on the case.
- Ambient temperature were values gathered for Kuwait during summer days as displayed in Abdal (2022)
- Indoor temperature was set at 23°C
- Pressure drop across each system components was neglected
- Compressor isentropic efficiency (η_{comp}) was assumed to be 80%
- Subcooling (T_{sc}), superheat (T_{sh}) and pinch-point temperatures (T_{pinch}) were set to 5°C, 5°C, and 5°C, respectively

In general, most archival articles (Bahman et al., 2018; Bahman, 2018; Tello-Oquendo et al., 2016; H. Lee et al., 2013; D. Lee et al., 2015; H. Cho et al., 2009; I. Y. Cho et al., 2016; Chung et al., 2018; Siddharth et al., 2004; Kang et al., 2008; Kim, Song, et al., 2018; Kim, Jeon, et al., 2018; Luo et al., 2020; Roh et al., 2014; Shuxue et al., 2013; B. Wang et al., 2009; X. Wang et al., 2009; Xu et al., 2013; Yang et al., 2021; Zhang et al., 2016; Fan et al., 2020) provided the experimental parameters used to calculate the COP of AC and refrigeration cycles that were tested. The model herein was used to estimate the parameters in the cases where they were omitted from the references.

2.4 VI system correlation development

The COP of an AC system is strongly influenced by the ambient dry-bulb and wet-bulb temperatures and system's evaporation and condensation temperatures. Therefore, an empirical correlation between the mentioned temperatures and the VI system's COP was derived from the literature data gathered by Abdal (2022) in the following section. The various temperatures were used as input variables, while the COP was considered as a single output variable. The Multi-Fit software (Bell & Bach, 2020) was used to develop the correlation and derive an equation to represent the COP in terms of ambient temperature, condensation temperature, and evaporation temperature. In addition, two more empirical formulas were developed to investigate the effect of including ambient wet-bulb temperature on system COP.

2.4.1 Empirical COP equation derivation

Data collected from literature, found in Abdal (2022), were compiled and organized to present the effect temperature parameters have on the VI system's cooling COP. The literature data, namely ambient temperature (T_{amb}), condensation temperature (T_{cond}), and evaporation temperature (T_{evap}), were fitted accordingly using the Multi Fit software (Bell & Bach, 2020) to predict the VI system's COP. Because all the reported data were sampled at an optimal compressor's intermediate injection pressure (the square root of the multiplication of evaporation and condensation pressures), the systems studied are operating at optimal conditions and the maximum COP is achieved all the time. Therefore, the injection state can be omitted in the regression process. The refrigerant type was also excluded from the correlation due to its limited effect. The empirical formula developed went through multiple trials and fittings to accurately encompass all VI cooling cycles. The empirical equation of COP is expressed as following:

$$\begin{aligned}\mathrm{COP} \; &= 13.8T_{amb}^{-0.25} - 1.64\times10^{-1}T_{cond}^{0.95} - 5.83\times10^{-1}T_{evap}^{1.01} + 4.47\times10^{27}T_{amb}^{1.44}T_{cond}^{-18.51}T_{evap}^{-0.69} + 5.2\times10^{-2}T_{cond}T_{evap} \\ &-4.2\times10^{-2}T_{amb}T_{evap} + 2.5\times10^{-3}T_{amb}T_{cond} - 9\times10^{-4}T_{cond}T_{evap}^{2} - 3.2\times10^{-4}T_{cond}^{2}T_{evap} + 1.4\times10^{-3}T_{amb}T_{evap}^{2} \\ &-8.57\times10^{-6}T_{amb}T_{cond}T_{evap} + 8.085\times10^{-6}T_{amb}T_{cond}^{2} + 2.4\times10^{-4}T_{amb}^{2}T_{avap} - 2.6\times10^{-5}T_{amb}^{2}T_{cond}\end{aligned} \tag{4}$$

Eq. (4) presents the relationship COP has to the parameter temperatures in the form of a first-degree order polynomial equation with 3 cross terms. The number of terms in the equation above was limited to the least number of terms to include the widest range of temperature parameters. and resulted in a determination coefficient (R^2) and a mean absolute error (MAE) of 0.992 and 3.807%, respectively.

2.4.2 COP correlation with the effect of wet bulb temperature

It is necessary to develop an equation that encompasses the wet bulb temperature to have accurate COP results during humid and cold weather for the air-cooling process. The wet bulb temperature measures how much water vapor the atmosphere can hold and in turn dictates the evaporation temperature in the cooling cycle. Eqs. (5) and (6) are different variations of COP correlations that include the wet bulb temperature parameter (T_{wb}). Eq. (5) produces more accurate results, with MAE of 1.2%, but only can applied for extreme outdoor ambient temperatures. Whereas Eq. (6) resembles a wider range of data collected to generate the empirical equations and can be applied during a wider range of weather conditions. Eq. (5) was developed using the data set gathered by Abdal (2022) and it is fitted to the first-degree order with one cross term. The equation has an R^2 and MAE of 0.98 and 1.2%, respectively. The proceeding Eq. (6) was developed using the data set gathered by Abdal (2022) and it is fitted to a first order equation with no cross terms. Moreover, Eq. (6) has an R^2 of 0.96 and an MAE of 2.29%.

$$\mathrm{COP} = -5.94 + 1.79\times10^{2}T_{cond}^{-0.0078} - 1.49\times10^{2}T_{evap}^{-0.00079} + 2.051\times10^{2}T_{amb}^{-0.008} - 2.19\times10^{2}T_{wb}^{-0.0052} \tag{5}$$

$$\mathrm{COP} = 3.52\times10^{-9}T_{cond}^{4.44} - 23T_{evap}^{0.34} + 16.4T_{amb}^{0.26} + 21.6T_{wb}^{-0.33} + 135.46T_{cond}^{-0.423}T_{evap}^{0.84}T_{amb}^{-2.51}T_{wb}^{1.56} \tag{6}$$

2.5 Annual COP analysis and assumptions

Eq. (4) was used to calculate the COP of an AC system with VI used during Kuwait's summer months. Using ASHRAE standards (ASHRAE, 2009), the indoor temperature and relative humidity were set to 24°C and 50% respectively.

According to the equation $T_{evap} = T_L - T_{sh} - T_{pinch}$, the evaporation temperature used was 14°C, assuming the pinch point and subcooling temperatures were 5°C and 5°C, respectively (Bahman et al., 2014; Barghash et al., 2021). The ambient weather temperatures simulated are represented in Abdal (2022), whereas the condensation temperatures were calculated from $T_{cond} = T_H + T_{sc} + T_{pinch}$ (Bahman et al., 2014; Barghash et al., 2021).

3. RESULTS AND DISCUSSION

3.1 Validation of empirical COP correlations

The data gathered to generate the correlation of COP was compiled from a dataset consists of a total of 101 data points that provide the COP and parameters of the cooling systems (Bahman et al., 2018; Bahman, 2018; Tello-Oquendo et al., 2016; H. Lee et al., 2013; D. Lee et al., 2015; H. Cho et al., 2009; I. Y. Cho et al., 2016; Chung et al., 2018; Siddharth et al., 2004; Kang et al., 2008; Kim, Jeon, et al., 2018; Luo et al., 2020; Roh et al., 2014; Shuxue et al., 2013; B. Wang et al., 2009; X. Wang et al., 2009; Xu et al., 2013; Yang et al., 2021; Zhang et al., 2016; Fan et al., 2020). After the COP equation was developed, it was reapplied to the data sets to estimate the accuracy of the predicted COP results. When the empirical COP Eq. (4) was applied to data gathered in Abdal (2022), results showed that the predicted COP using the new correlation was within an 8% error of the actual COP data from the literature. The generated Eq. (4) was validated through comparison with the collected experimental data. Only a total of 4 data points resulted in COP that were in error range higher than 8%. The 4 data points were related to D. Lee et al. (2015) and Kim, Song, et al. (2018); Kim, Jeon, et al. (2018) works found in Abdal (2022). These higher errors can be justified due to the ambient temperature of 25°C or lower. Since the focus was improving cooling at high temperatures, especially in Kuwait, the data sets with lower ambient temperatures below 25°C failed to produce consistent results for COP. Empirical Eqs. (5) and (6) were applied to the experimental data, and the results proved the new correlations were within 5% and 10% error of the actual COP data, respectively. The reason for higher error in Eq. (6) (*i.e.,* 10% error) was due to the limited literature cases that included wet bulb temperature parameters in their studies. To be noted that the literature available for the topic of VI in cooling mode are scarce in comparison to heating mode. As more studies are conducted and data are available, the generated COP correlation in this study can be improved and modified.

3.2 Application of empirical COP correlation to Kuwait case

A monthly average of COPs for a typical year for Kuwait's weather was produced using the empirical formulas derived in this study. Furthermore, an hourly analysis of COP during a typical day for each month was conducted for Kuwait case with the use of the empirical formulas of COP developed.

3.2.1 Monthly average COP performance for a typical year

The trend produced after applying Eq. (4) to Kuwait's weather is shown in Fig. 2. The COP had a minimum value during the month of July due to the highest ambient temperature in the year and increased for the rest of the other months. The months of January, February, and December were omitted because the AC systems were mostly switched off due to cold weather during those months reaching a temperature as low as 10°C in the city and 70% relative humidity during the month of December. Fig. 2 indicates that there is a noticeable advantage to using the VI technique in the hot weather of Kuwait. As evident form the figure, the VI system improved the COP of the cooling cycle in Kuwait by 34% during July in comparison to the conventional system. This is mainly due to the increase in cooling capacity and decrease in power consumption, and therefore improve COP using VI system. In addition, no significant improvement was observed during the spring (March and April) and autumn months (October and November) due to colder outdoor temperatures and the limited applicability of VI technique, which only resulted in an average decrease of 5%. However, with a better control of the injection state, the performance of the VI system can match or even surpass the conventional one.

3.2.2 Hourly COP performance for a typical day in each month

A thermal performance study was performed to analyze an AC system's COP during a typical day in Kuwait for every month. The 21st day of each month was chosen as a typical day because it represents the day Kuwait recorded the highest ambient temperature during July (KMC, 2020 (accessed January 21, 2022)). The results derived in Fig. 3 resulted from Eqs. (4) to (6). During the summer and hot months Eq. (4) was used to compute the COP, while during more humid and cooler months an average of Eqs. (4) to (6) was used to compute the final COP. Fig. 3 shows that the same COP trend for every month where the hottest time during a day in Kuwait was about 2 PM and the coolest time was about 4 AM. It can also be indicated that throughout the year the COP of the VI cooling cycle remained efficient and well above what is considered the basic efficient COP cooling threshold for harsh hot climate as of Kuwait.

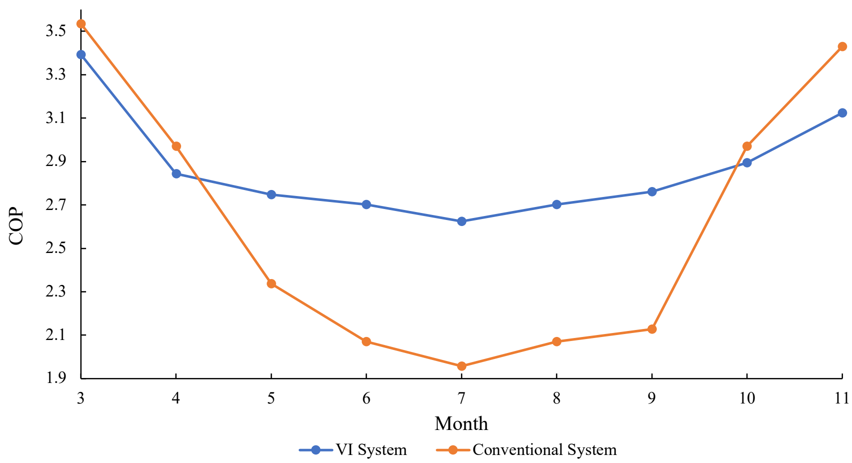

Figure 2: Results comparison of vapor injection (VI) and conventional vapor compression cycle (VCC) system for monthly cooling coefficient of performance (COP) using the developed empirical equations for Kuwait weather.

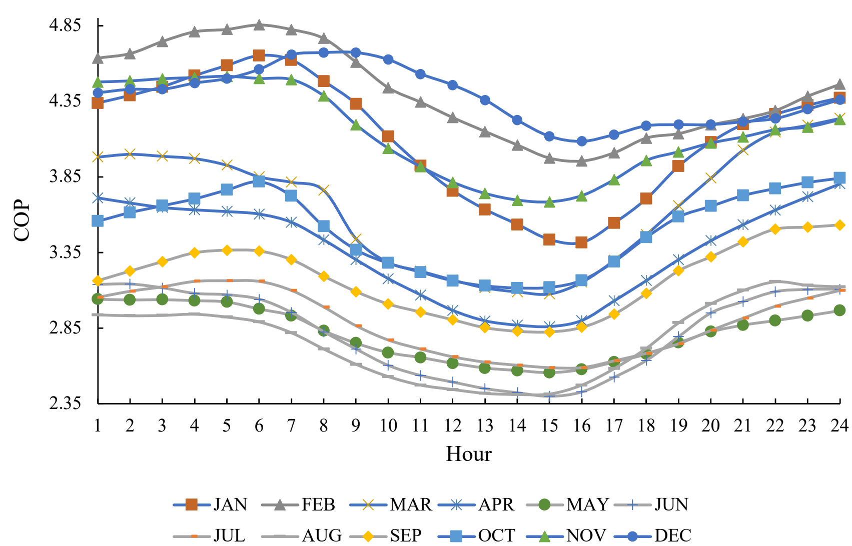

Figure 3: Cooling coefficient of performance (COP) using the vapor injection (VI) system during 24 hours of the 21st of every month for Kuwait weather.

4. CONCLUSIONS

This study assesses the implementation of the vapor injection (VI) technique to the cooling cycle operating in hot ambient climate such as Kuwait. Numerous literature studies provided experimental evidence of the improvement of VI system has on cooling air in relatively warm weather up to 30°C. However, only few researches studied the effect of VI on the cooling process in hot and harsh weather similar to Kuwait. A literature review was conducted to sample all the data for the VI cooling systems operating at high ambient temperatures along with the weather data for Kuwait to accurately calculate the performance improvement of VI system compared to the conventional one for residential applications. The conventional baseline system was modelled using a simplified thermodynamic analysis to better understand the influence of VI has on the cooling process during the hot season. Several empirical correlations were developed pertaining to the VI systems' coefficient of performance (COP) using literature experimental data for the operating conditions (evaporating temperature T_{evap} and condensing temperature T_{cond}) as well as ambient conditions (dry bulb temperature T_{amb} and wet bulb temperature T_{wb}). The correlations were validated, tested, and resulted in relatively accurate predictions. The correlations have also been exercised to predict the monthly and daily COP improvement of implementing the VI technique under Kuwait weather conditions during the summer season. The study yielded the following main results:

- Three empirical correlations for the COP of the VI system were developed using literature experimental data (first equation as a function of T_{evap}, T_{cond} and T_{amb} including all sampled data; second equation as a function of T_{evap}, T_{cond}, T_{amb} and T_{wb} including only summer ambient conditions; third equation as a function of T_{evap}, T_{cond}, T_{amb} and T_{wb} including only conditions as low as 21°C) showed relatively accurate predictions with mean absolute errors of 3.81%, 1.2%, 2.29%, respectively.
- The developed correlations were exercised for a case study of Kuwait where the VI system showed a COP improvement of up to 34% during the typical month of July.
- The scarce amount of data available for VI technique applied to the cooling processes limits the examined operating ranges in this study. Therefore, it is recommended to conduct further experimental studies for the VI system operating at extreme hot ambient conditions to expand it to the Gulf Cooperation Council (GCC) countries.

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