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FEASIBILITY OF COMBUSTION TURBINE INLET AIR-COOLING IN THE ARABIAN GULF REGION

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ABSTRACT

Combustion turbine inlet air-cooling systems (CTIACS) have been implemented in various regions around the globe and have displayed proven results in terms of their effectiveness and economic feasibility. Nonetheless, these systems have been rarely employed in the Arabian Gulf region with such existing installations are still undergoing continuous evaluation. The main objective of this study is to highlight the associated benefits of employing a CTIACS option in UAE. This is achieved by first exploring the weather patterns in UAE in order to propose proper weather design conditions. Moreover, the impact of a CTIACS is presented, for a prescribed inlet air temperature, on the annual gross energy increase, average heat rate reduction, cooling load requirements and net power increase. Finally, a combustion turbine unit with a relatively small mass flow rate is shown to be very much feasible economically even upon reducing inlet air temperature below the ISO rating.

INTRODUCTION

The performance of a combustion turbine is inherently tied to the ambient air conditions. Gas turbine output suffers significantly at increased temperature levels due to the reduced available combustion air mass flow rate. On the contrary, cooled denser air gives the system a higher mass flow rate and pressure ratio; resulting in an increase in combustion turbine output. Usually, this is accompanied by an overall increase in the system efficiency due to the suppression in the heat rate. In addition, the emission per kWh is reduced as lower exhaust temperatures are maintained. This will result in reducing the environmental impact of such units. Recently, combustion turbine inlet air cooling systems (CTIACS) have received considerable attention giving that it is a viable design option in increasing power output. Such cooling systems bring the combustion turbine (CT) units to operate close to manufacturer design condition and in some cases independently of climatic conditions.

The available technologies today are classified either under evaporative cooling or refrigerative type systems. Generally speaking, evaporative type systems are suitable for hot and dry climates since its cooling capability is limited to the wet bulb temperature value. This places a cap on the recovered power (10-15% at most in dry regions). However, it has several advantages such that it requires minor modifications to the inlet house, low capital installation cost (US$50-100/kW), and it carries a high reliability and a low O&M cost. On the contrary, refrigeration systems are complex and require a high capital investment (US$200-400/kW) and O&M cost. However, its application is not limited by the wet bulb value and, thus, higher power augmentation can be achieved (15-25%). Several investigations have reported on the current available technologies and their associated economic feasibility studies. De Lucia et al. (1993), Loud et al. (1996), Jolly et al. (1998) and Stewart (1999) have all, among others, discussed various methods that are currently employed for cooling the inlet air. Also, they have highlighted the economic factors relevant to introducing such options into a combustion turbine system. Indeed, the installation and running costs must be weighed against the expected revenues generated from the additional gained output. Furthermore, Daryl et al. (1996) presented the effect of thermal energy storage (TES) system on CTIACS economics and identified the preferable storage technologies for different applications. The growing interest in the field has also prompted the recent formation of the Turbine Inlet Cooling Association (TICA) in Illinois, USA. Other societies, such as ASHRAE, have formed taskforce groups to follow up on the feasibility of this vital technology.

CTIACS IN THE ARABIAN GULF REGION

Despite its growing popularity in the gas turbine plants, CTIACS have not been implemented on a wide scale in the Arabian Gulf region. This region, which is located in the southwestern part of the Asian continent, comprises of six Arabian countries on the western side of the Gulf (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and UAE) and Iran being on the eastern side. The region is summoned by several common patterns. These include severe summer conditions (hot and humid in the coastal areas becoming hot and dry inwards toward the arid areas), scarce water resources (58% of the world desalinated water is produced in this region). The region also hosts the largest oil and natural gas reserves in the entire world. Moreover, the region has shown a great demand for electric power in the past decade due to the rapid growth in the industrial and commercial sectors. Increased domestic consumption of electricity coupled with volatile swings in peak loads, have soared demand for electric power in the region. This phenomenon is further escalated giving the relatively low and flat energy rates (~ US$0.041/kWh), which is heavily subsidized by the local governments. The United Arab Emirates (UAE) alone, for instance, has invested over 1.2 billion dollars last year in the electricity and potable water generation sector.

Many of the region states have undertaken measures for deregulating and privatizing the power generation industry to lift the burden associated with the installation expenditures of new units to meet the hike in electric power demand. The total electric power generation in the region is estimated at 46.5 GW (Bahrain 1.1 GW, Kuwait 9.3 GW, Oman 2.1 GW, Qatar 1.9 GW, Saudi Arabia 25 GW, and UAE 7.1 GW) with an expected annual growth of 4%. It is worth noting that the generating capacity for Saudi Arabia alone is forecasted to double by 2020 at a cost of more than 4.5 billion dollars per year. The rapid development in the region has also brought acute need for costly expatriates to execute the evolving projects. Giving the nature of the projects, the expatriates have the tendency to heavily rely on packaged imported technologies that in many cases are not catered to climatic design considerations suitable for the region.

The power stations in the region are mainly comprised of combustion turbines and combined cycle plants with diesel units as emergency backups. The CT units are widely used for base and peak loads. They are heavily favored owing to the relatively cheap input fuel cost, which is abundantly available in the region. It is roughly estimated that at least sixty five percent of the total installed generating units in the region are gas turbine based. This should definitely build an appreciation for the need to tackle the problem of power output deficiency during hot periods. In addition, the problem needs careful study as the region is divided into a coastal humid region and arid inland dry zone. Although the information at hand is sketchy, several attempts were made to incorporate CTIACS in the current stations in place. Again, the proposed systems are typically imported pre-engineered packaged technologies that might not necessarily meet expectations.

Currently, a refrigeration cooling system based on ice storage with a peak cooling capacity of 190,000 TOR tons of refrigeration (668,230 kW) is already in the evaluation phase in Al-Qaseem plant in Saudi Arabia. The system is intended to boast the output of 6 new GE frame 7EA combustion turbines from 57 MW each in peak summer condition to 77 MW each turbine. This project is reported to carry a price tag of less than US$200 per kW output gain. Hence, thorough insight into the climatic design information is a necessary step before committing to any CTIACS option. Caution must be exercised, however, in selecting a suitable system as evaporative coolers, for instance, tend to degrade in performance with increased humidity. Although evaporative media-type cooling system is not favored in humid climates, such a system was recently installed in the coastal city of Dubai, UAE.

Our survey of the literature has shown that most of the reported studies have either focused on highlighting available technologies in the market or were tailored to the implementation of a given CTIACS in a particular station. Definitely, there exists a lack of information on the most suitable CTIACS in terms of effectiveness and economic feasibility in a broad region. Such a study might ultimately recommend a blend of CTIACS's to meet the various design conditions. Thus, this study in an attempt to identify the weather pattern zones in the Arabian Gulf region. However, the current study will focus on UAE owing to the limited weather data details available for the rest of the region at the moment. The undertaken measures in this study though maybe systematically extended to other countries once their weather data are obtained. Our chief objective here is to categorize the weather information in UAE, in particular, for a typical year in terms of dry bulb temperature (DBT), wet bulb temperature (WBT) and the computed atmospheric enthalpy (h) values. Such information is typically limited to a few of the main cities in the country. Upon identifying the weather patterns, the main characteristics of a typical CTIACS option will be explored. The current study is concluded by portraying a design chart that identifies the degree of the economic feasibility of the selected CTIAC for a broad range of CT mass flow rates.

DESIGN CONSIDERATIONS

The selection of a CTIACS for a particular station would require studying the behavior of several key design factors. These include ambient DBT and enthalpy values, ratio of airflow to turbine output, turbine performance in terms of power output and heat rate, and the expected hours of operation. Often, the design enthalpy condition is overlooked by the DBT condition. This will lead to significant flaws in estimating the size of the selected system. In fact, the design condition should be specified in terms of the maximum registered values for DBT and WBT that will correspond to the maximum enthalpy value in a given time slot. Accordingly, this will present the upper bound from which cooling should take place. Also, it is equally important to state the lower bound for the cooling level. Some stations design the size of the chosen CTIACS on the cooling capability to reach the ISO condition at 59°F (15°C). A designer might be even tempted to increase the power output above the rated capacity by cooling the inlet air below ISO condition. However, such an attempt would be running the risk of ice formation on the bell-mouth, which might flake off to ultimately damage the compressor blades. Furthermore, the revenues generated from the additional increase in output power upon suppression of inlet air temperature to ISO condition or even lower might not be worth the investment to begin with. The designer should carefully select the cooling range where maximum power increase can be attained.

WEATHER PATTERNS

The actual weather data in UAE for the year 2000 was chosen as a basis for performing the analysis in this study. Upon mapping the weather information obtained for the different geographical areas, three distinct weather patterns were recognized. Moreover, these weather patterns were found to fall under three main cities, namely; Al-Ain (Pattern I), Abu Dhabi (Pattern II) and Fujairah (Pattern III). Giving the massive number of data at hand, the daily weather data for each pattern was categorized in a one-degree intervals while the analysis of energy, power and heat rate is based on five degrees..

Fig. 1 represents the cumulative hours per year for the recorded DBT and WBT values in the three patterns considered. The qualitative assessment of the data indicates that pattern I is very hot and relatively dry, pattern II very hot and humid, and pattern III hot and very humid. This is not surprising giving that pattern I represents the inward arid areas while pattern II and III represent the coastal area lying on the Arabian gulf and Oman gulf, respectively. The figure also shows that the margin between DBT and WBT for pattern I is noted to be the highest. In addition, pattern I tends to enjoy low WBT values which would encourage the application of evaporative cooling over the refrigerated one and the vice versa is true for pattern III. It is interesting to note that although patterns I & II portray higher DBT values, the frequency of registered DBT values between 95-110°F (35.0-34.3°C) in pattern III is much higher. Another observation is that DBT registered in pattern III was associated with higher WBT than other patterns for approximately 50 percent of the annual hours, which signals the existence of long periods of high humidity levels.

Pinpointing such observations are crucial in understanding a given weather pattern, which ultimately aids in the selection process of the most suitable CTIACS. On top of this, Fig. 1 is very beneficial in terms of identifying the number of hours that inlet air cooling can be achieved to a prescribed cooling set point. For instance, if the desired cooling temperature is 75°F (23.9°C), the cooling hours for patterns I, II and III will be 6150, 5240, and 6387 hours, respectively. However, if the prescribed cooling point is further lowered to 65°F (18.3°C), a CTIACS under patterns I, II and III will be in operation for over 89%, 83% and 98%, respectively, of the total annual available hours. These depicted hours clearly indicate that the CTIACS will be required to operate for quite long hours or even continuously around the year depending on the prescribed inlet air temperature. It is evident that the longer operation hours will bring about higher power output recovery and, consequently, better feasibility of the system. Table 1 lists the operating envelope for the different weather parameters in the three patterns based on the actual weather data. The mean value is the arithmetic average of the parameter over the summer period June-September (total 2928 hours). One may deduce from Table 1 that weather pattern I is considered to be the hottest (highest mean value of DBT) while weather pattern III is the wettest (highest mean value of WBT) and, accordingly, the highest mean value of enthalpy. The maximum values recorded for DBT, WBT and *h* in Table 1 will be considered as the design condition for each corresponding pattern.

Table 1. Operating weather envelope.

Pattern	DBT (°F)			WBT (°F)			*h* (Btu/Ib)		
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
I	120	50	97	83	45	70	47	18	34
II	120	50	94	90	45	77	55	18	40
III	110	58	93	91	50	82	57	18	46

Fig. 2 demonstrates the cumulative hours of computed ambient enthalpy (*h*) for the three patterns. It can be seen from the results that pattern III has more than double the accumulated hours of high enthalpy values [over 40 Btu/lb (167.4 kJ/kg)] as compared to the other patterns. This difference is even more pronounced for higher *h* values. This is attributed to the relatively lower DBT and higher WBT values registered under this pattern. Since inlet air cooling may be attempted to a baseline enthalpy of, for example, 25 Btu/lb (104.7 kJ/kg), the potential for a year round CTIACS operation in the different patterns is vivid.

INLET AIR TEMPERATURE OPTIMIZATION

In order to develop an appreciation for the implementation of CTIACS, a sample case study is examined under the proposed design ambient condition for the different patterns. A simple-cycle industrial CT is considered in this regard with an inlet air flow rate of 35 lb/hr/kW (15.9 kg/hr/kW). In addition, the power output and the heat rate variation against the inlet air temperature (IAT) were accounted for based on the documented report work of

Katipamula and Brown (1999). Moreover, a cooling system was incorporated with an assumed average Coefficient of Performance (COP) of 4.0, which is typical for water chiller systems. The estimated annual gross energy increase per MW output under ISO rating is plotted against the desired IAT for the three patterns as depicted in Fig. 3. Overall, all three patterns were found to score similar gross energy gains for the given IAT range with pattern I attaining the highest values for IAT greater than 60°F (15.6°C). The annual gross energy increase under pattern III is noted to slightly surpass pattern I for IAT values less than 60°F (15.6°C). In addition, pattern III results show almost null increase in annual gross energy for IAT ≥ 100°F (37.8°C) while it picks up noticeably for lower IAT values. An increase by 2.3, 2.56 and 2.71 folds can be attained for patterns I, II and III, respectively, if IAT is lowered from 80°F to 65°F (26.7 to 18.3°C). Of course, the additional gain in annual energy should be weighed against the expenses associated with the consumed energy to overcome cooling load requirements. Thus, the annual consumed energy based on the predicted cooling load was annexed to the figure at hand.

The consumed energy predictions follow a similar trend to that of the gross increase. At an IAT of 65°F (18.3°C), the consumed annual energy to the gross increase values for patterns I, II and III represents 14.6%, 20.5% and 23.8%, respectively. The relatively higher energy consumption estimated for patterns III is attributed to the frequent recording hours of DBT in the range of 95-110°F (35.0-43.3°C) that coincide with high WBT as stated earlier. This will subsequently prolong the CTIACS operating hours to reach the desired IAT of 65°F (18.3°C). In a similar manner, the average reduction in the annual heat rate and the corresponding fuel saving are depicted in Fig. 4. The fuel cost for natural gas was taken at a rate of 1.1 US$/$10^6$ Btu (US$/293kWh). The results show a significant reduction in the heat rate for a CT located in any of the three patterns once lower IAT values are taken into consideration. For example, an increase of over 3 folds is achieved in all patterns for incorporating IAT values up to 65°F(18.3°C) as compared to 85°F (29.4°C).

COOLING SYSTEM CHARACTERISTICS

The above observations prompt us to further examine the implementation of the selected CTIACS in the different weather patterns. The cooling capacity for the chosen CTIACS to achieve a desired IAT for each pattern is shown in Fig. 5. The figure also displays the net power increase in kW per MW (ISO) at the desired IAT. It should be mentioned that the consumed (parasitic) power is calculated based on 25 Ib/hr/kW (11.3 kg/hr/kW) air flow rate and, again, an overall COP of 4.0 for the cooling system. The results show that the different patterns considered to be governed with similar characteristics. As illustrated in the figure, the cooling load is inversely proportional to the desired IAT value. In general, cooling load requirements tend to be insignificant up to the dew point temperature (DPT) of the ambient air. This is due to the fact that the cooling load requires merely sensible heat removal. Accordingly, the estimated parasitic power in this range tends to increase slightly with the decrease in IAT. Further reduction in the desired IAT will require moisture removal, which will bring up the contribution of the latent load into picture. The latent load dominates the overall cooling load requirements once IAT dips below the DPT owing to the massive amount of moisture to be removed. Consequently, the parasitic power consumption increases remarkably, which will negatively impact the net power increase as depicted by the reduction in its slope for IAT less than DPT.

Clearly, the DPT for any pattern plays a detrimental role in the desired IAT value if high net power increase is sought. In this regard, pattern III demonstrates the least increase in the net power output while demand the largest cooling capacity, which is attributed to the onset of latent load at the relatively high IAT of 91°F (32.8°C). At the same token, patterns I and II give equal net power increase for IAT ≥ 82°F (27.8°C). Upon further reduction an appreciated discrepancy is for net power increase is attained, which is attributed to the higher DPT for pattern II. The net power increase for the different patterns is shown to attain the same proportions for IAT ≤ 60°F (15.6°C). It is worth noting that the CTIACS operating at IAT equals to 50°F (10.0°C) recovers up to 240 kW/MW (ISO) under pattern I, 210 kW/MW under pattern II, and only 170 kW/MW under pattern III. These values corresponds to a net power increase of 24%, 21% and 17% net power increase, respectively.

ECONOMIC FEASIBILITY OF CTIACS

The current study is wrapped by examining the feasibility of incorporating a refrigerative cooling system for different CT mass flow rates. The capital installation cost of such a cooling system is currently estimated at an average price of US$ 2000/TOR (~US$ 570/kW). With the new installation cost of a CT operating under a simple-cycle configuration being currently around US$ 400-600/kW, it is possible to construct a 'feasibility chart' that outlines the domain where the installation of a CTIACS can be economically justified. This feasibility chart is illustrated in Fig. 6 for a CT located in pattern I with different mass flow rate (Q) scenarios. All flow rates scenarios are shown to fall below the US$ 400/kW (based on the capital investment) for IAT greater than DPT with the ones with low Q values being the most feasible. This is expected giving that the CT is sensitive to the amount of Q values. Furthermore, attempts to further cool below the DPT show that the CT's with the relatively high Q values to exceed the installation kW cost limit. This becomes even more pronounced if it is intended to reduce IAT below the ISO rating of 59°F (15.0°C) as suggested in several previous studies. It is obvious that the economic return of the net output gain is offset by the escalation in the cooling system capacity, which results in a higher investment cost.

CONCLUSIONS

The main objective of this study is to increase awareness on the importance of incorporating CTIACS options into the Arabian gulf region, in general, and UAE, in particular, based on sound analyses and economic evaluations. The investigation is also aimed at studying the weather data information in UAE for the sake of establishing weather patterns in different zones and, accordingly, proposing weather design conditions. This will assist greatly in examining the sensitivity of the CT performance with respect to the inlet air temperature. The analyses were based on an industrial CT operating under base load mode, which is a common practice in this particular region. Another objective is to explore the impact of a CTIACS option for a desired IAT under different weather patterns on the annual gross energy increase, average heat rate reduction, cooling load requirements and net power increase. Moreover, the results show high economic feasibility for installing a CTAICS option when operating at a desired IAT value, which is in close proximity to the design DPT. Furthermore, it is suggested that the desired be set to a constant prescribed inlet air temperature to ensure smooth operation, especially for base load CT units. What is more, a CT with a small mass flow rate value was found to be very much feasible economically even upon reducing IAT below the ISO rating.

In general, it is recommended that the desired IAT to be set between 60-75^{o}F (15.6-23.9^{o}C) for a good return on the CTIACS capital investment. The gains in the net power output would be highly appreciated if the current flat rate for energy bills, which is adopted in most Arabian Gulf countries, is altered in favor of scheduled charges as practiced in the many other countries. This shall make the savings obtained in output power more beneficial to power plant authorities, which will accordingly bring more attention to incorporating CTIACS options. Finally, it is highly recommended to extend the current study to cover the rest of the region given the significant number of continuously installed combustion turbines. Such a study will be greatly viable once pertinent information related to weather conditions and the performance characteristics of the operating combustion turbines are obtained.

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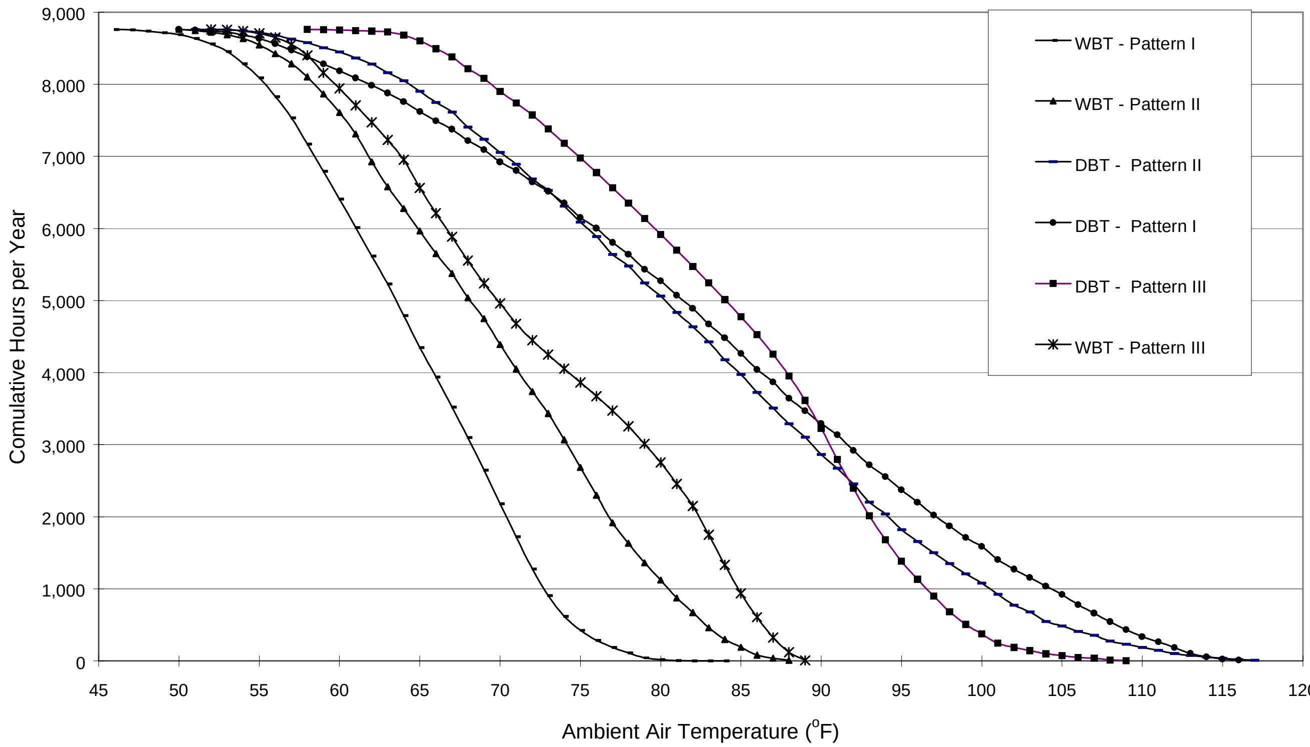

Fig. 1. Annual cumulative hours recorded for DBT and WBT under the three weather patterns.

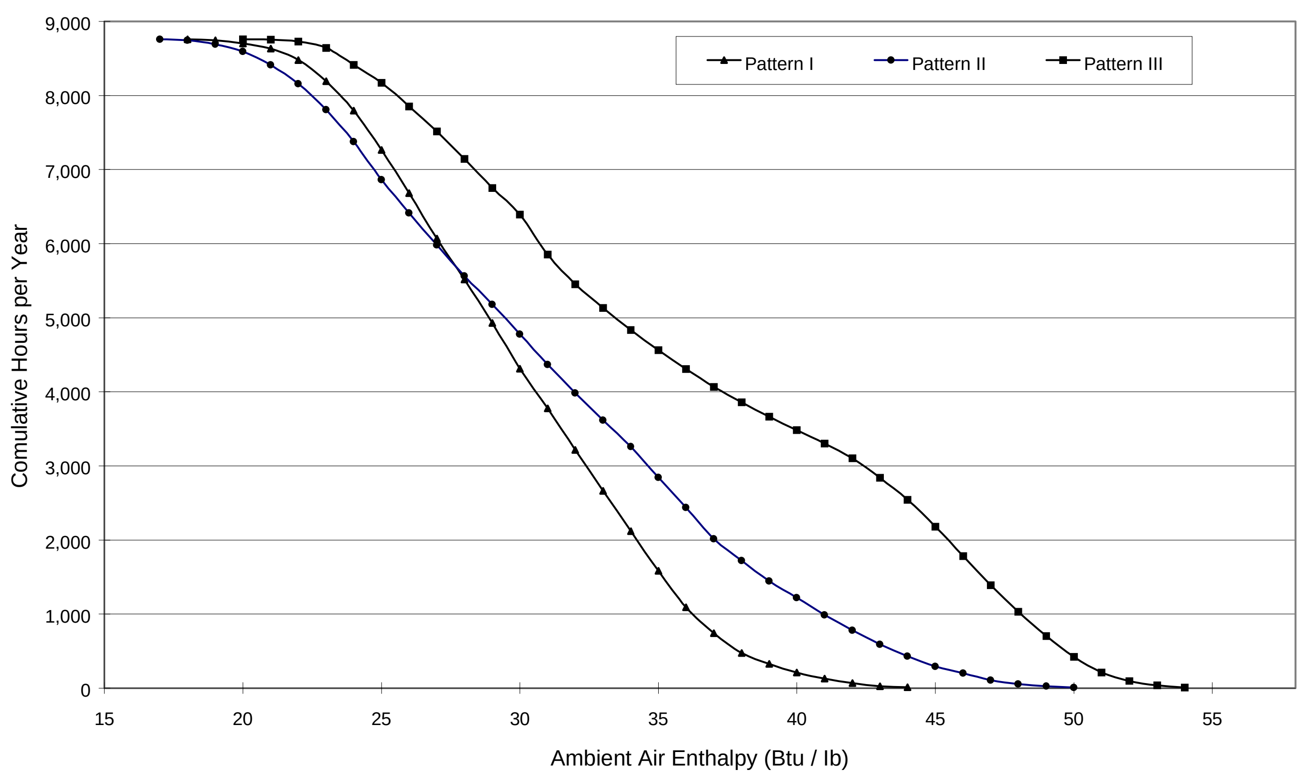

Fig. 2. Annual cumulative hours recorded for enthalpy under the three weather patterns.

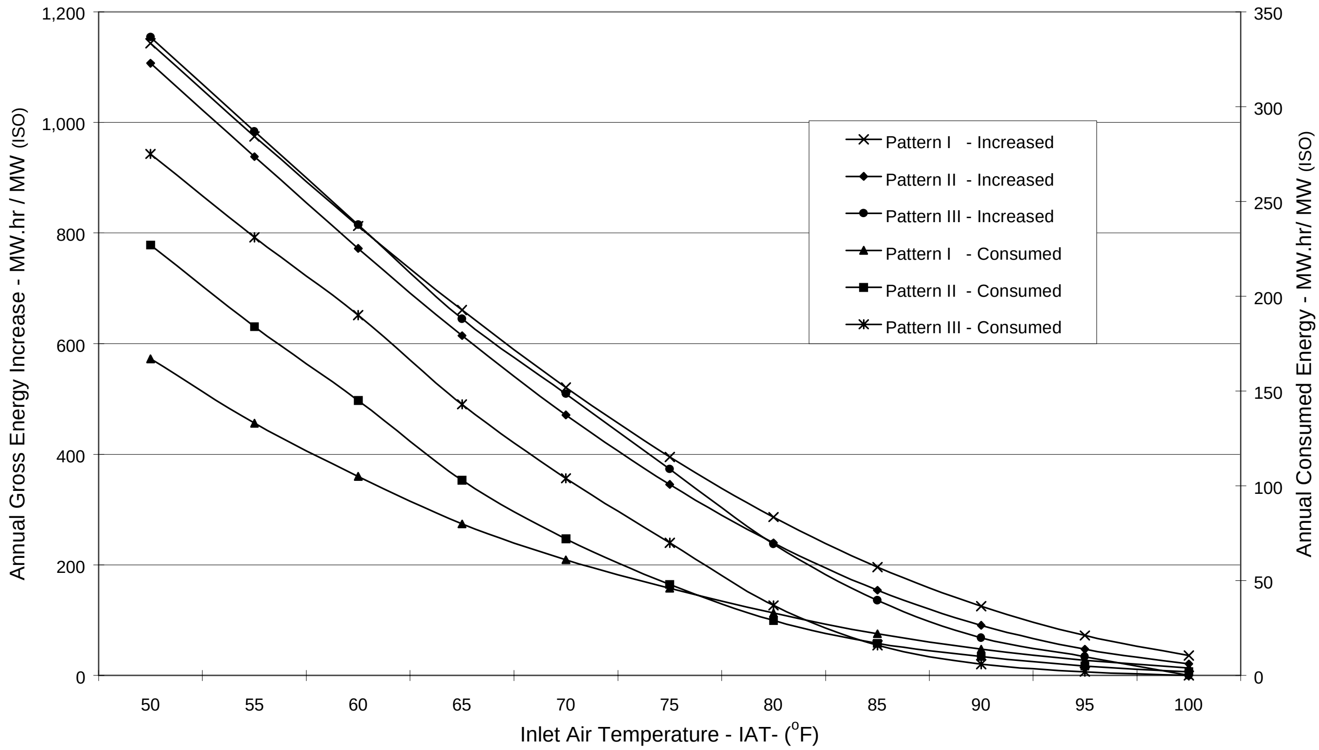

Fig. 3. Variations of the annual gross and consumed energy predictions for different desired IAT.

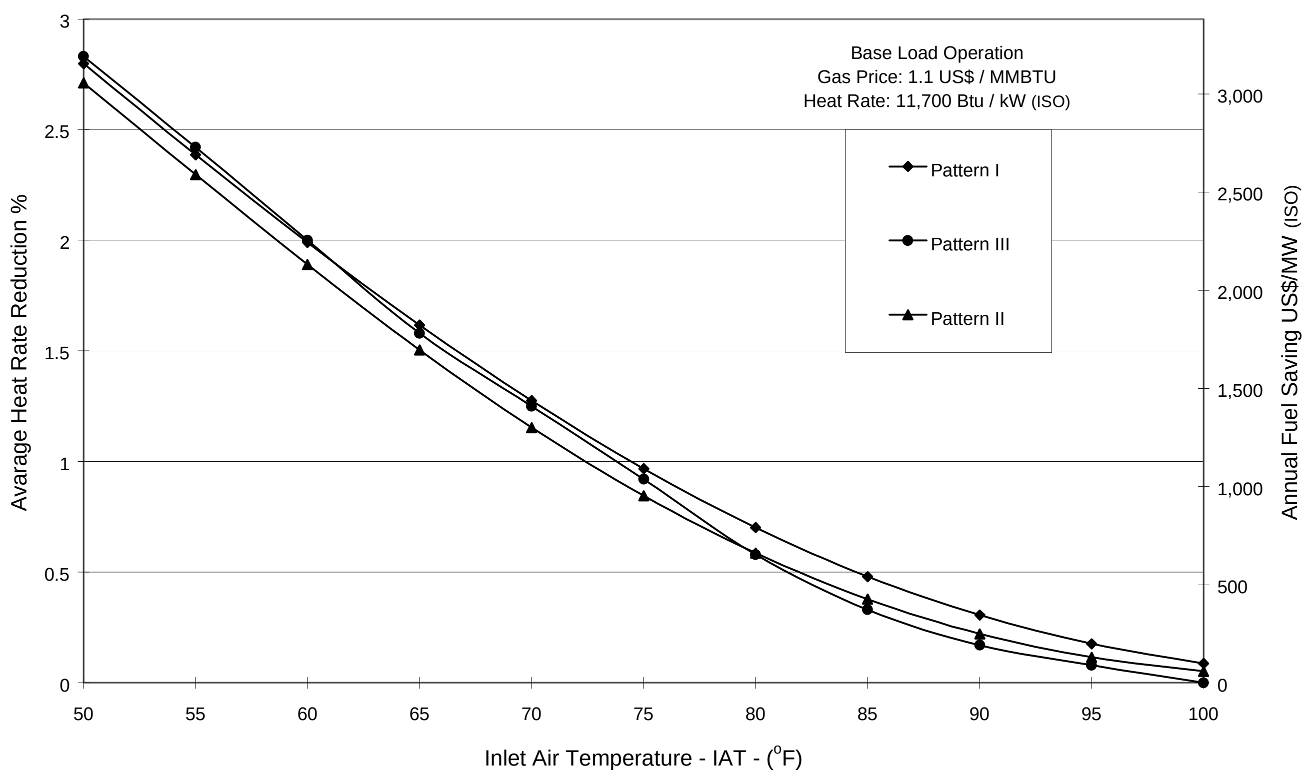

Fig. 4. The percentage average heat rate reduction and the corresponding annual fuel saving for different desired IAT.

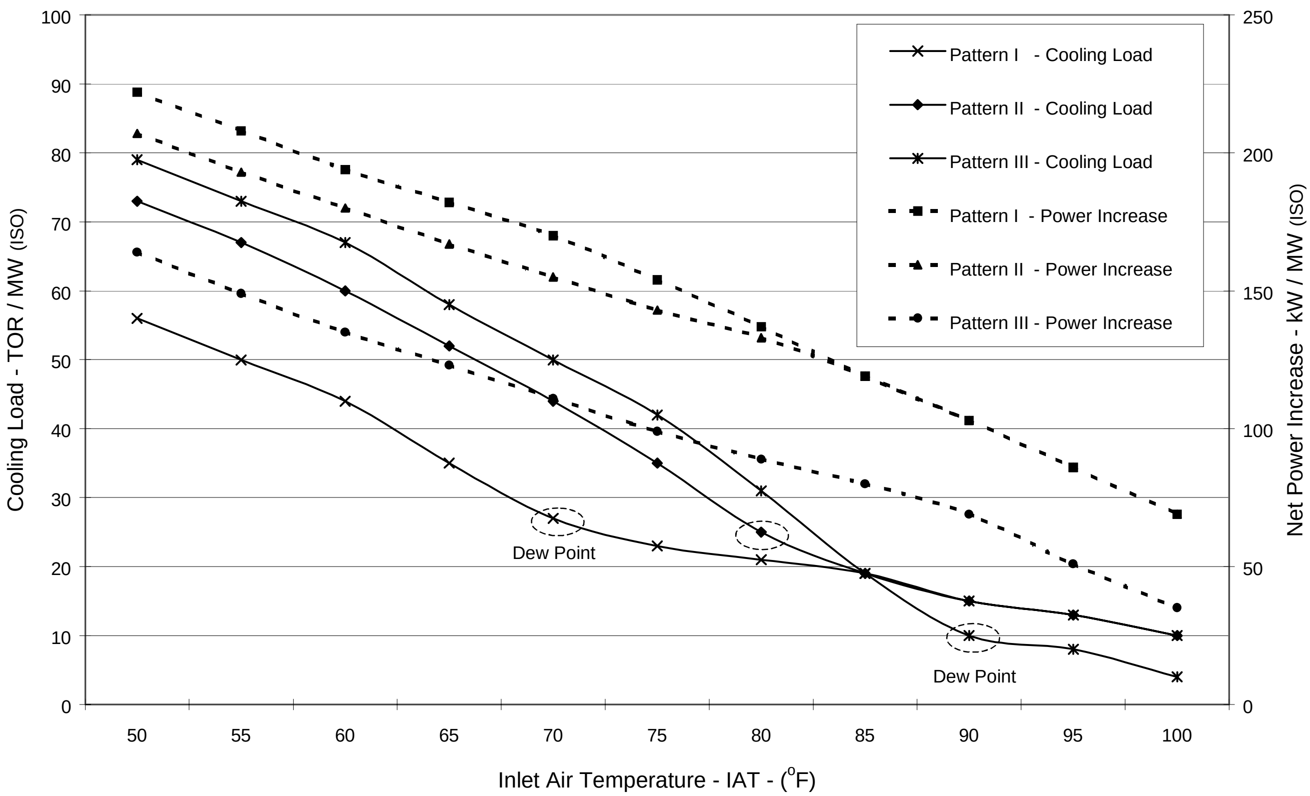

Fig. 5. The cooling load demand and the net power variation for different desired IAT.

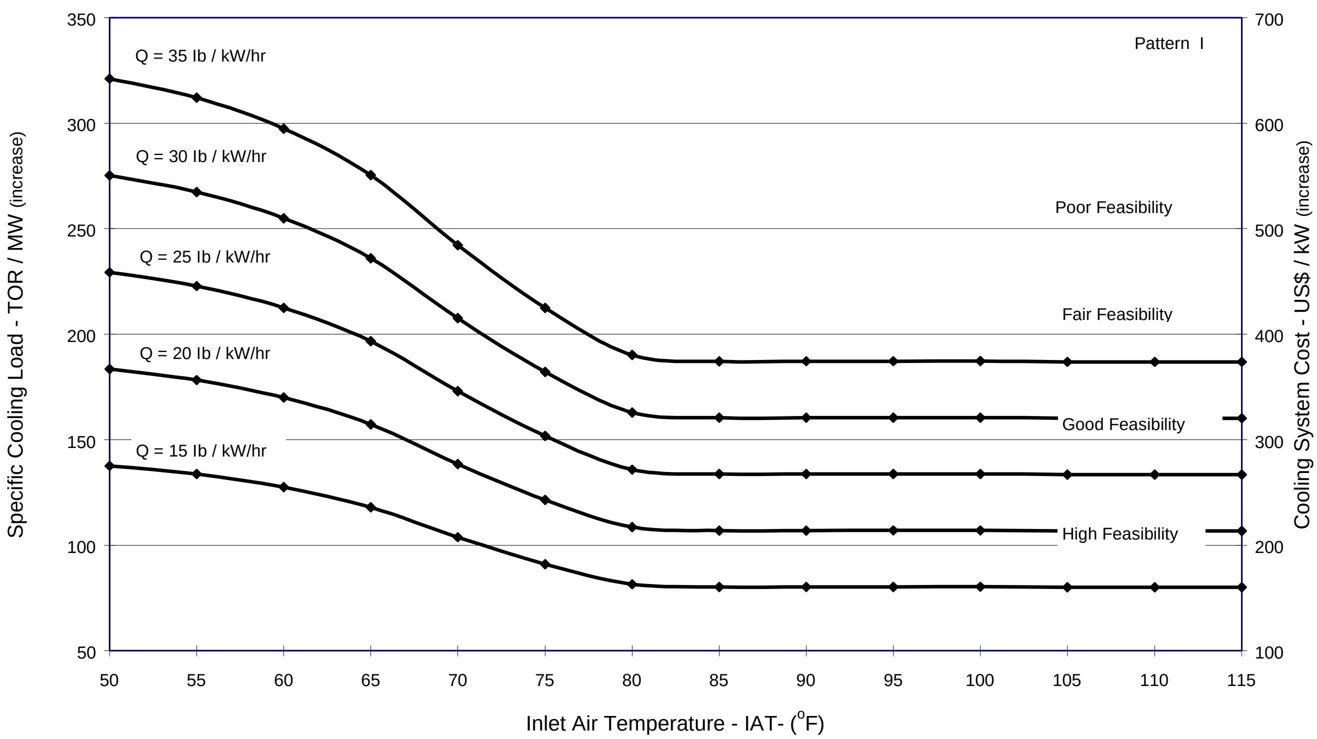

Fig. 6. Economic assessment of a cooling system operating under different desired IAT.