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NUMERICAL SIMULATION OF GE 7001 EA GAS TURBINE USING EXPERIMENTAL DATA FOR COMPRESSOR INLET AIR COOLING

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ABSTRACT

In this paper computer Simulation of GE 7001 EA gas turbine that widely used in the kingdom of Saudi Arabia is reported. Simulation is done using cooled air data obtained previously from different experiments. These data are used as input to the compressor to see its effect on the output power and efficiency of the gas turbine. GE 7001EA gas turbine, (GE7121EA models) is simulated using THERMOFLEX software. The specifications of this type of turbines are built in this software. This type of gas turbine model is used in Riyadh and Taif power stations. ISO conditions and actual weather conditions are used for simulations. The results show that the maximum increase in the net power output is about 12, 6 and 5.8% depend on the used cooling data. On the other hand, the maximum percentage increase in efficiency is turned to about 2.5, 1.3 and 0.9 respectively.

INTRODUCTION

Gas turbines have been used for power generation in several regions in the world. Different geographical locations have different climatic conditions (average temperature and humidity), which will affect the performance of the gas turbine power plant. In the Kingdom of Saudi Arabia, electrical power generation is experiencing increased seasonal demand due to air conditioning use. Over the last two decades, increasing demand of power, lack of water and short time erection favoured the installation of gas turbines (GT) at different locations in KSA. The output of a gas turbine decreases as the ambient temperature increases. This is because the mass flow rate of air decreases as the air becomes less dense at higher ambient temperatures. Since the output of a GT is proportional to the airflow, a reduction in the airflow would cause a reduction in the output. In addition to output, the heat rate degrades with an increase in the ambient temperature. Ali et al. [1] have recently reported a new evaporation technology which used to humidify the air for cooling before it enters the compressor of a gas turbine. In their results, a wind tunnel was built and a matrix of four MiniModule membrane contactors was used as a test section where water pumps through (cross flow heat exchange). The relative humidity, temperature and pressure losses were measured before and after the test section. The air velocity over the test section and the water flow rates through the contactors were measured and the effectiveness of cooling and humidification were also determined. Furthermore, Zeitoun et al. [2] have used the same test rig of [1] where the test section was a matrix of porous ceramic tubes for air cooling by humidification. The relative humidity, pressure loss, air velocity and water velocity were measured before and after the test section. Heat and mass transfer analyses were made. Results show that the proposed technology has an efficiency not to exceed 45%. Ali et al. [3] have extended the work of [1] where the test section was a tray covered with a specific membrane and full of water where the air passed over it. This paper uses General Electric (GE) 7001 gas turbine for numerical simulation of the experimental data presented by [1], [2] and [3] for air cooling. The ISO gas turbine condition is used as a benchmark for comparison.

Cooling the air at compressor inlet is a well known technology used to increase the gas turbine capacity and efficiency. Air humidification can be used to cool the air at compressor inlet. This technology is inexpensive, simple to apply and its power consumption is low. Now, the humidification is carried out by spraying water in air flow upstream of the compressor inlet. Using this method requires high quality water to avoid corrosion and erosion of the compressor blades, and scale off composition on compressor blades. Furthermore, droplets drift can increase water consumption in humidification process. Membrane evaporation is a new technology used in many applications including desalination, juice concentration, etc. Using this technology in air humidification eliminates blade problems mentioned above and droplets drift. In addition, low quality water can be used in humidification process. Inlet air cooling markedly enhances the performance of combustion turbines [4-9]. Various approaches to cooling the turbine inlet air have been employed. The two most common approaches (evaporative cooling and mechanical refrigeration) have been extensively applied, and are well developed and documented. Combustion turbines have ambient temperature sensitivity: both the capacity and the efficiency decrease as the ambient temperature increases. The power demand of the compressor section of the turbine is proportional to the absolute temperature of the inlet air. The compressor capacity is proportional to the density of the inlet air, which is inversely proportional to the absolute temperature. Therefore higher ambient temperatures negatively affect both capacity and efficiency of the turbine. The turbine manufacturers supply curves detailing with both the power output and the heat rate as a function of ambient temperature.

Erickson et al. [6] reported a 300-refrigeration ton aqua ammonia refrigeration unit is required to cool the inlet of a 5 MW gas turbine from 35°C to 5°C. This cooling increase the power output by 1 MW, and the added power is at a marginal efficiency of 39%, compared to 29% for the base turbine power. Alhazmy and Najar [8] reported that the spray coolers appear to be capable of boosting the power and enhancing the efficiency of the gas turbine power plant in a way that is less expensive than cooling coils. Although the performance of spray coolers is deeply influenced by the ambient temperature and humidity, they operate efficiently during hot and dry climatic conditions. The analysis of Alhazmy and Najar [8] have shown that the spray cooler reduces the temperature of incoming air by 3–15 ^{o}C, enhancing the power by 1–7% and improving the efficiency by 3%.

The Membrane evaporation is a new technology which utilizes the evaporative cooling technique in air conditioning, water desalination, juice concentration and other applications [10-15]. Microporous hydrophobic membranes have been examined by Loeb [10] for possible use as containers in the evaporative cooling of water, particularly in desert climates. The potential of using hollow fiber membranes in evaporative cooling applications for space air conditioning has been reported by Johnson et al. [11]. Their results showed that reasonable numbers of fibers and membrane surface area could provide cooling effectiveness comparable to the conventional evaporative cooling equipment. Experimental and theoretical investigation of air humidification/dehumidification processes were carried in a hollow-fiber membrane contactor by Bergero and Chiari [16]. Their experimental results indicate high mass transfer efficiency for both humidification and dehumidification.

Recently, Zhang [17] has reported numerical and experimental study about parallel-plates membrane cores used in air-to-air heat exchangers for fresh air heat and moisture recovery. His results indicated that for those membrane structures, when the channel pitch is below 2 mm, the flow distribution is quite homogeneous and the sensible and latent heat performance deteriorations due to flow mal distribution are below 9% and can be neglected. However, when the channel pitch is larger than 2 mm, the maldistribution is quite large and the consequent thermal and latent performance can be deteriorated by 28%. More recently, a numerical simulation for mass transfer through a porous membrane of parallel straight channels has been reported by Lu and Lu [18]. In their study, two types of flows, channel flow and ultra-filtration flow, have physically described. Their results have displayed the flow and solute distribution patterns inside channels, described the ultra-filtration profiles along the surface of the porous membrane and disclosed an existent nano-scale reverse osmosis problem. Ceramics and ceramic matrix composites for heat exchangers in advanced thermal systems has been reviewed by Sommers et al. [19]. In their paper, the current state-of-the-art of ceramic materials for use in a variety of heat transfer systems has reported. Coupled heat and mass transfer in a counter flow hollow fiber membrane module for air humidification has been reported numerically and experimentally by Zhang and Huang [20]. Their results showed good matching between the numerical and experimental humidification and cooling effectiveness. In another study, Zhang [21] has shown the heat and mass transfer characteristics of fibers bundle in aligned and staggered arrangement in air cross flow. The flow maldistribution and the consequent performance deterioration in a cross flow hollow fiber membrane module used for air humidification have been studied by Zhang et al. [22]. Their results showed that the packing fraction affects the flow maldistribution substantially. It should also mentioned that other methods of cooling the inlet air is known as wet media evaporative cooling technology, which offer 85 to 90% of evaporation efficiency, may not require high water quality but they need huge amount of water. These methods offer reduced risk of erosion to the compressor blades and corrosion to turbine inlet duct structure. It should be noted that the current suggested method of research presents a new interesting engineering concepts to enhance the performance of the gas turbine in spite of its low efficiency. Therefore, further researches need to be performed to improve the efficiency of the proposed technology, such as increasing the number of MiniModule membrane contactors array, which leads to the increase of exchange surface between the membrane and airflow. Other advantage; is that the possibility of using recycled water (chemically treated water) since the fresh quality water in desert area such as Saudi Arabia is mostly available through the desalination plants and commonly used for human beings supply.

This paper uses the cooled air data obtained from the experiments of [1-3] as inputs to the compressor of the gas turbine unit. GE 7001EA gas turbine model is used for the simulations where THERMOFLEX software is used.

Nomenclature

GT	Gas turbine
LHV	Low heating value

HHV	Higher heating value
ISO	International Organization for Standardization
RH	Relative humidity
T	Temperature

THERMOFLEX SOFTWARE [23]

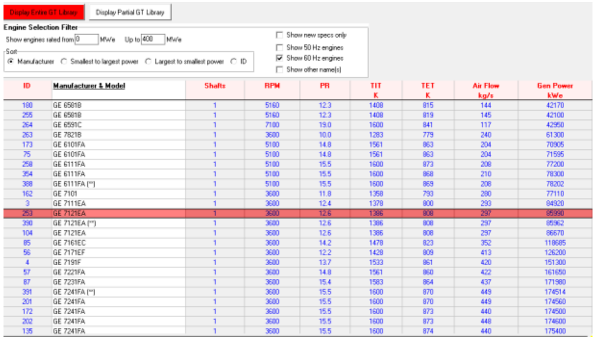
THERMOFLEX (part of THERMOFLOW software) is a modular program with a graphical interface that allows you to assemble a model from icons representing over one hundred and seventy-five different components. The program covers both design and off-design simulation, and models all types of power plants, including combined cycles, conventional steam cycles, and repowering. It can also model general thermal power systems and networks. It answers the need of some customers for a single, "jack-of-all-trades" program.

In addition to being a comprehensive, stand-alone tool, THERMOFLEX may be used in conjunction with Thermoflow's application-specific programs to provide powerful synergies. GT PRO plant designs can be directly loaded into THERMOFLEX. Composite models built partly in GT PRO, GT MASTER, and THERMOFLEX can be created to extort the best of the Application-Specific and Fully-Flexible approaches to plant modeling. For gas turbine simulation, this software gives the capability to:

1- Simulate actual gas turbines from different manufacturers, the software contain a library for different gas turbine models, see table below.
2- Simulate selected gas turbine model under design and off design conditions.
3- Off design simulation for selected gas turbine model can be carried out at different inlet conditions.

COMPUTER SIMULATION RESULTS

The GE 7001EA gas turbine, (GE7121EA models) is simulated using THERMOFLEX software. The specifications of this type of turbine are built in this software as seen in Fig. 1. GE 7001EA gas turbine model is widely used in Riyadh power stations. This simulation is done under ISO conditions and at actual weather conditions. Figures 2(a) and 2(b) show the Thermoflex model of this type of the turbine and the method of selecting the model type within the Thermoflex, respectively.



Show engines rated from 0 MWe Up to 400 MWe

Sort: ● Manufacturer ○ Smallest to largest power ○ Largest to smallest power ○ ID

☐ Show new specs only
☐ Show 50 Hz engines
☑ Show 60 Hz engines
☐ Show other name(s)

ID	Manufacturer & Model	Shafts	RPM	PR	TIT K	TET K	Air Flow kg/s	Gen Power kWe
180	GE 6581B	1	5160	12.3	1408	815	144	42170
255	GE 6581B	1	5160	12.3	1408	819	145	42100
264	GE 6591C	1	7100	19.0	1600	841	117	42950
263	GE 7821B	1	3600	10.0	1283	779	240	61300
173	GE 6101FA	1	5100	14.8	1561	863	204	70905
75	GE 6101FA	1	5100	14.8	1561	863	204	71595
258	GE 6111FA	1	5100	15.5	1600	873	208	77200
354	GE 6111FA	1	5100	15.5	1600	868	210	78300
388	GE 6111FA (**)	1	5100	15.5	1600	869	208	78202
162	GE 7101	1	3600	11.8	1358	793	280	77110
3	GE 7111EA	1	3600	12.4	1378	800	293	84920
253	GE 7121EA	1	3600	12.6	1386	808	297	85990
390	GE 7121EA (**)	1	3600	12.6	1386	808	297	85962
104	GE 7121EA	1	3600	12.6	1386	808	297	86670
85	GE 7161EC	1	3600	14.2	1478	823	352	118685
56	GE 7171EF	1	3600	12.2	1428	809	413	126200
4	GE 7191F	1	3600	13.7	1533	861	420	151300
57	GE 7221FA	1	3600	14.8	1561	860	422	161650
87	GE 7231FA	1	3600	15.4	1583	864	437	171980
391	GE 7241FA (**)	1	3600	15.5	1600	870	449	174514
201	GE 7241FA	1	3600	15.5	1600	870	449	174560
172	GE 7241FA	1	3600	15.5	1600	873	440	174500
202	GE 7241FA	1	3600	15.5	1600	873	448	174600
135	GE 7241FA	1	3600	15.5	1600	874	440	175400

Figure 1. Gas turbine library of THERMOFLEX

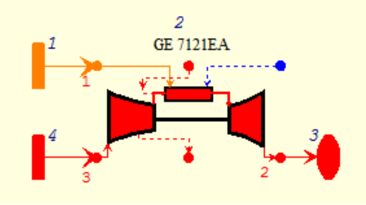
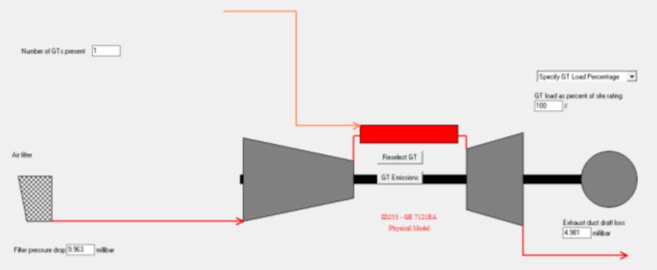


Figure 2(a). Thermoflex model of GE 7001EA gas turbine



Number of GTs present 1

GT load as percent of site rating 100 %

Filter pressure drop 9.963 millibar

Exhaust duct draft loss 4.981 millibar

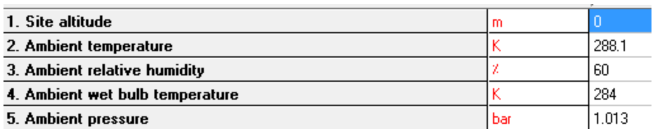
Figure 2(b). Selecting gas turbine in Thermoflex

Steps for simulation:

1- Selecting gas turbine model, for example select GE 7001EA gas turbine. The specifications of this model of turbine are built in this software. Figure 3.1 shows Thermoflex model of this type of turbine.
2- Select frequency of 60 Hz similar to Saudi Arabia power plant output.
3- Select type of Fuel
4- Select type of simulation: design or off design condition
5- Apply inlet conditions

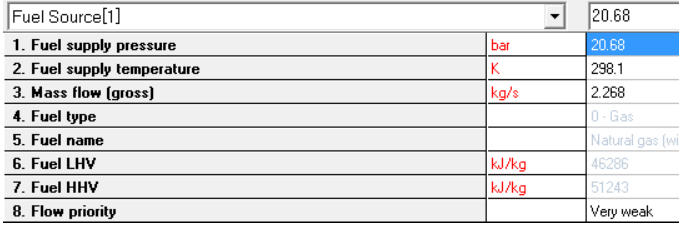
The current frequency is assumed 60 Hz in the current simulation similar to Saudi Arabia power plant output. The GE gas turbine performance at ISO conditions are listed in Table 1. For this test, natural gas fuel is used in this simulation. Properties of natural gas are shown in Table 2. The simulation outputs are shown in Table 3. The ISO net power of this type of the turbine is 83837 kW. The net heat rate and efficiency, based on LHV, is 11088 kJ/kWh and 32.47%, respectively.

Table 1. ISO conditions



1. Site altitude	m	0
2. Ambient temperature	K	288.1
3. Ambient relative humidity	%	60
4. Ambient wet bulb temperature	K	284
5. Ambient pressure	bar	1.013

Table 2. Fuel type and inlet conditions



Fuel Source[1] ▾		20.68
1. Fuel supply pressure	bar	20.68
2. Fuel supply temperature	K	298.1
3. Mass flow (gross)	kg/s	2.268
4. Fuel type		0 - Gas
5. Fuel name		Natural gas (wi
6. Fuel LHV	kJ/kg	46286
7. Fuel HHV	kJ/kg	51243
8. Flow priority		Very weak

The experimental data of [1-3], obtained by cooling the air are used as input to the compressor of the gas turbine keeping the other data which selected for GE 7001EA from the library of the THERMOFLEX as seen in Fig. 1. Table 4 shows the relative humidity and the temperature before and after the test sections at different water and air velocities. Figure 3 shows these simulations as bar charts for the net power developed using the cooled air and compared with that of no cooling and the ISO condition. It is clear from this figure that using the current experimental data increases the net power output compared to that with no cooling. It should be observed that this increase in the developed power is approaching the ISO condition. Figure 4 used the same data in Table 4 to compare the efficiency of the gas turbine using cooled air with that of the GE 7001EA model. It is interesting to show that the efficiency increases with the cooled air and approaching the ISO condition. The percentage increase in the net output power using the cooled air corresponding to the experimental data taken from Table 4 is presented as bar charts in Figure 5(a) and verses the inlet cooling temperature drop in Fig. 5(b). This figure shows that the last two experiments of the first test membrane [1] gave the highest efficiency followed by the runs M1/5, M1/4, M1/2, and M1/1 respectively. The runs of the second and third [2, 3] membrane M2/2 and M3/15 give also a remarkable increase in the output power. Figure 5(b) shows the percentage increase in the net output power increases as the drop of the inlet air temperature increase. Similar figure for the percentage increase in the net efficiency versus the air temperature drop is shown in Fig. 6, where the percentage of the net efficiency increases as the air temperature drop increases.

CONCLUSIONS

Simulation of the experimental data was done using the data of the GE 7001 EA gas turbine widely used in the kingdom. This simulation showed an increase in the power output and the efficiency of the gas turbine using the experimental cooled air. The maximum increase in the net power output is 12%. On the other hand, the maximum percentage increase in efficiency is about 2.5. The experimental data shows that ceramic tube membrane technology [1] could be implemented for gas turbine inlet air cooling without concerns of compressor blades erosion due to water droplets associated with water spray technology (also known as fogging technology). However, more researches need to be performed to improve the efficiency of the proposed technology.

ACKNOWLEDGMENTS

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Table 3. Plant Summary at ISO conditions

Ambient pressure	bar	1.013
Ambient temperature	K	288.1
Ambient RH	%	60
Ambient wet bulb temperature	K	284
Gross power	kW	84858
Gross electric efficiency(LHV)	%	32.86
Gross heat rate(LHV)	kJ/kWh	10954
Net power	kW	83837
Net electric efficiency(LHV)	%	32.47
Net heat rate(LHV)	kJ/kWh	11088
Net fuel input(LHV)	kW	258210
Net process output	kW	0
CHP efficiency	%	32.47
PURPA efficiency	%	32.47
Plant auxiliary	kW	1020.6
Net electric efficiency(HHV)	%	29.33
Net heat rate(HHV)	kJ/kWh	12275
Net fuel input(HHV)	kW	285864
Energy chargeable to power	kW	258210
Electric efficiency on chargeable energy	%	32.47
Generator of Gas Turbine(GT PRO) power	kW	84858
Gas Turbine(GT PRO) misc. auxiliary	kW	172
Specified additional misc. auxiliary	kW	848.6
Shaft-1 net power	kW	86153

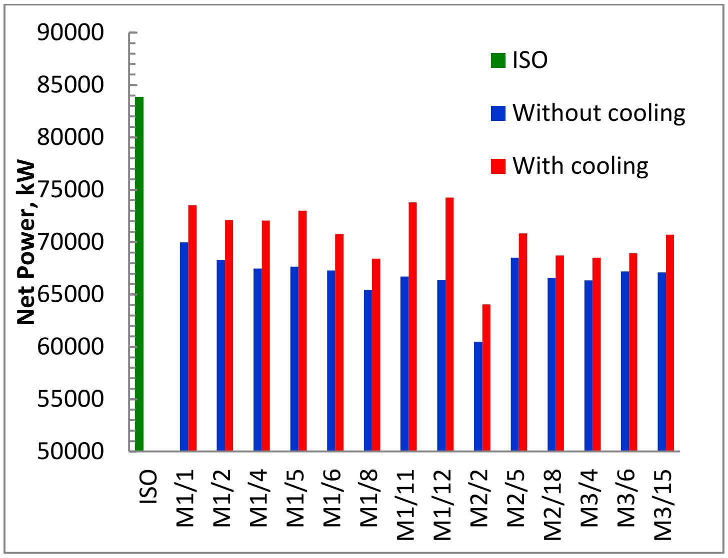

Figure 3. Effect of membrane evaporative cooling on GE 7001EA gas turbine net power for runs listed in Table 4

Table 4. Experimental data used for simulations.

First membrane [1]	Water velocity	Air velocity	Before test section		After test section	
	m/s	m/s	T, ^{o}C	R.H, %	T, ^{o}C	R.H, %
M1/1	0.0167	3.52	34.86	5.57	28.10	7.06
M1/2	0.0226	3.52	37.63	4.27	30.83	5.81
M1/4	0.0344	3.52	39.37	2.65	30.93	4.28
M1/5	0.0167	3.61	38.64	5.67	29.14	8.55
M1/6	0.0229	3.61	39.21	3.42	33.42	5.30
M1/8	0.0343	3.61	42.16	2.68	37.41	4.16
M1/11	0.0286	4.03	40.08	7.98	27.61	9.75
M1/12	0.0340	4.03	40.63	7.31	26.73	9.08
Second Membrane [2]	Water flow rate kg/s					
M2/2	0	3.33	51.15	3.84	45.67	7.82
M2/5	0	5.04	37.15	9.89	33.31	13.48
M2/18	0.025	3.94	40.32	3.36	36.86	5.88
Third Membrane [3]	Angle					
M3/4	0	4.50	40.71	4.59	37.21	7.17
M3/6	5	2.98	39.31	8.34	36.46	11.01
M3/15	10	4.68	39.52	4.02	35.14	7.38

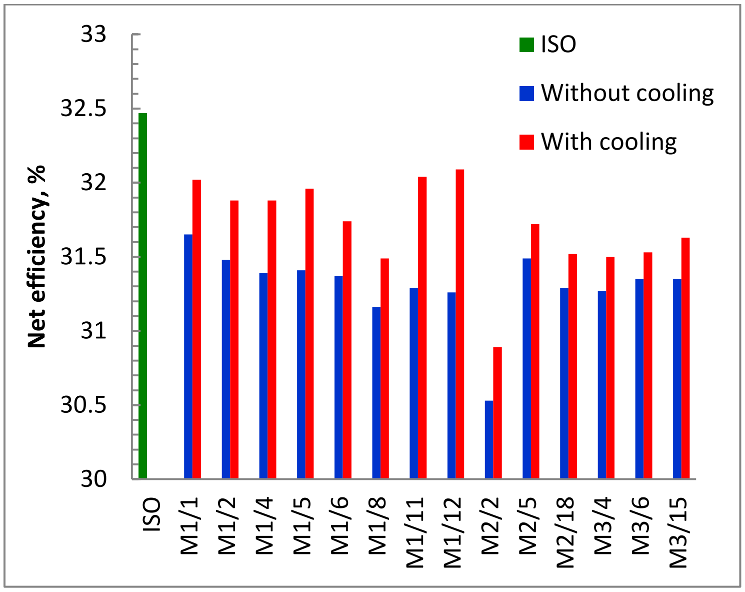

Figure 4. Effect of membrane evaporative cooling on GE 7001EA gas turbine net efficiency for runs listed in Table. 4.

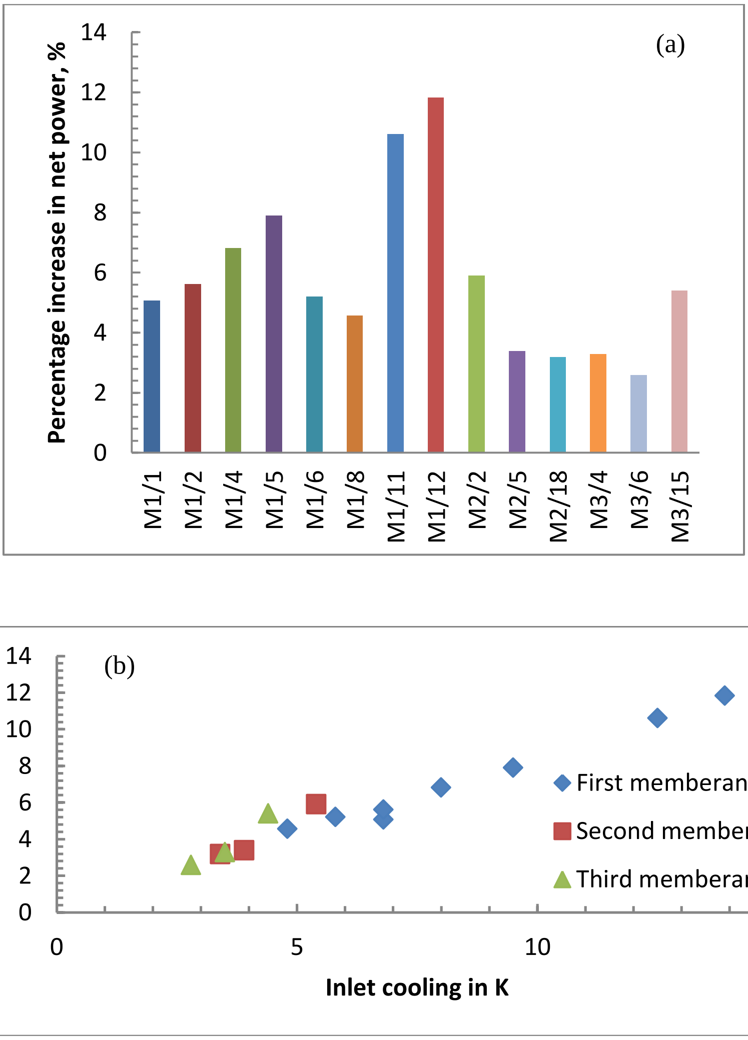

Figure 5. Increase in GE 7001EA gas turbine net power for the experimental runs shown in Table 4; (a) bar chart and (b) inlet cooling temperature drop.

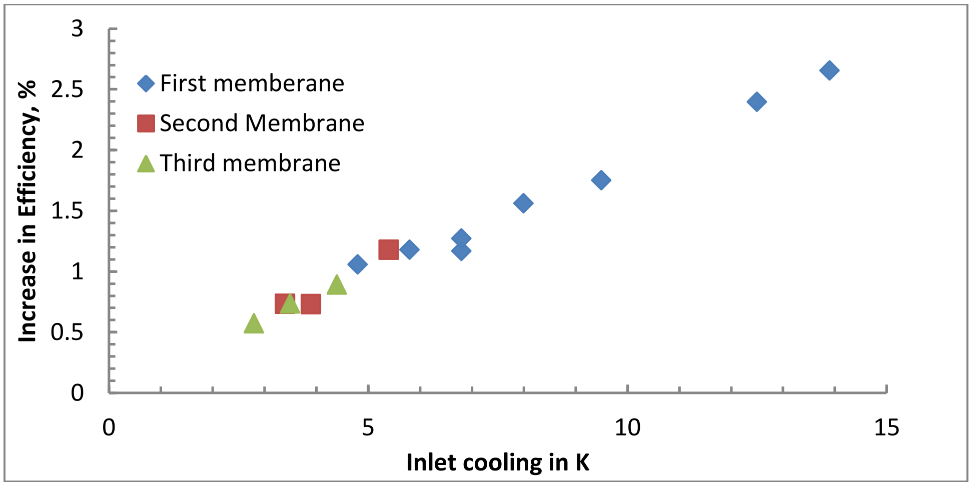

Figure 6. Increase in GE 7001EA gas turbine net efficiency versus inlet cooling temperature drop for runs listed in Table 4.

REFERENCES

[1] Ali, M, Zeitoun, O., Al-Ansary, H. and Nuhait, A., Humidification technique using new modified MiniModule membrane contactors for air cooling, *Advances in Mechanical Engineering*,Volume 2013, Article ID 174016, 11 pages, 2013.

[2] Zeitoun, O., Ali, M., Al-Ansary, H. and Nuhait, A, Ceramic tubes as a new humidification technique for gas turbine air cooling, In press, *International Journal of Thermal sciences*, 2014.

[3] Ali, M, Zeitoun, O., Al-Ansary, H. and Nuhait, A., Experimental study for air cooling using membrane covered tray, *Proceedings of the 5th International Conference on Porous Media and Their Applications in Science, Engineering and Industry*, June 22 – 27, 2014 at Kona, Hawaii, USA.

[4] Kumar, N. R., Krishna, K. R., Sita Rama Raju A. V., Improved Gas Turbine Efficiency Using Spray Cooler And Alternative Regenerator Configuration, ICRAMME 05, *Proceedings of the International Conference on Recent Advances in Mechanical &Materials Engineering* , 30-31 May 2005, Kuala Lumpur, Malaysia, Paper No.10.

[5] Jolly, S., Nitzken, J., Shepherd, D., Direct Spray System for Inlet Air Cooling W 501 B5", *Presented at the Power-Gen International* , Dallas, Texas – December 9-11, 1998.

[6] Erickson, D. C., Kyung, I., Anand, G., Makar, E. E., Aqua Absorption Turbine Inlet Cooler", *Proceedings of ASME International Mechanical Engineering Congress & Exposition* Washington, D.C., November 16-21, 2003.

[7] Punwani, D. V., Pasteris, R., *Cobined Cycle Journal*, Fourth Quarter,1-3 (2003).

[8] Alhazmy, M. M., Najjar, Y. S. H., *Applied Thermal Engineering* **24,** 415–429 (2004).

[9] Ameri, M., Hejazi, S. H., *Applied Thermal Engineering* **24,** 59-68 (2004).

[10] Loeb, S., *Annals of the New York Academy of Sciences*, **984,** 515-527 (2003).

[11] Johnson, D. W., Yavuzturk, C., Pruis, J., *Journal of Membrane Science,* **227**, Issues 1-2, 159-171 (2003).

[12] Bessarabov, D., Twardowski, Z., *Membrane Technology*, **2006**, Issue 7, 7-11 (2006).

[13] Drioli, E., Calabrd, V., Wu, Y., *Membrane distillation Pure & Appl. Chem*., **58**, No. 12, 1657—1662 (1986).

[14] F. Tillberg, "ZLD-systems An Overview", Department of Energy Technology, Royal Institute of Technology, KTH Stockholm, 2004.

[15] H. J. Zwijnenberg, G.H. Koops, M. Wessling, *Journal of Membrane Science*, **250**, 235-246 (2005).

[16] Bergero, S. and Chiari, A., Experimental and theoretical analysis of air humidification/dehumidification processes using hydrophobic capillary contactors, *Applied Thermal Engineering*, 21 (2001), pp. 1119- 1135.

[17] Zhang, L., Performance deteriorations from flow maldistribuion in air-to-air heat exchangers: A Parallel-plates membrane core case, *Numerical Heat Transfer, Part A*, 56 (2009) 746-763.

[18] Lu, J. and Lu, W., A numerical simulation for mass transfer through the porous membrane of parallel straight channels, *Int. J. of Heat and Mass Transfer*, 53 (2010) 2404-2413.

[19] Sommers, A., Wang, Q., Han, X., T'Joen, C., Park, Y., and Jacobi A., Ceramics and ceramic matrix composites for heat exchangers in advanced thermal systems- A r view, *Applied Thermal Engineering*, 30 (2010) 1277- 1291.

[20] Zhang, L. and Huang, S. Coupled heat and mass transfer in a counter flow hollow fiber membrane module for air humidification, *Int. J. Heat and Mass Transfer*, 54 (2011) 1055-1063.

[21] Zhang, L. Coupled heat and mass transfer in an application-scale cross-flow hollow fiber membrane module for air humidification, *Int. J. Heat and Mass Transfer*, 55 (2012) 5861-5869.

[22] Zhang, L., Li, Z., Zhong, T. and Pei, L., Flow maldistribution and performance deteriorations in a cross flow hollow fiber membrane module for air humidification, *J. of Membrane Science*, 427 (2013) 1-9.

[23] http://www.thermoflow.com/convsteamcycle_TFX.html