MODELING AND SIMULATION OF A TWO-STAGE AIR COOLED ADSORPTION CHILLER WITH HEAT RECOVERY

By
Firas Mahmoud Rashied Makahleh

Supervisor
Dr. Ali Abdel Al-Halim Badran, Prof

Co-Supervisor
Dr. Ayman Adnan Al-Maaitah, Prof

ABSTRACT

A theoretical study was developed for a two-stage adsorption chiller with an activated carbon/methanol pair. The objective of this work was to model the performance of such chiller and to compare it with the experimental work done by others. Such study will contribute to understand the working conditions of such chiller and lead to popularity of this chiller commercially. However, to design for larger capacity and to conduct a pre-operation detailed test, a simulation and modeling of such chiller needs to be conducted. No such studies have been done for this chiller so far so the need for larger capacity chillers and testing for various weather conditions still remains. As such, further work is necessary to establish theoretical model of this chiller so that capacity and performance could be easily predicted.

In this work, the following models were conducted numerically using MATLAB: modeling and simulation of the performance of two-stage adsorption chiller with and without heat recovery and then the models were validated by making comparison of the performance with experimental data for the two-stage adsorption chiller. The model was based on 10^{th} order differential equations; six of them were used to predict bed, evaporator and condenser temperatures while the other four equations were used to calculate adsorption isotherm and adsorption kinetics. This chiller is new patent chiller so the models results validated only with experimental data since no such model was built for the two stage air cooled adsorption chiller.

It was found that the simulation model results for the two stage air cooled chiller agreed well with experimental data in terms of cooling capacity (6.7 kW for the model against 6.14 kW for the experimental result at 30 °C cooling water temperature). The COP predicted by this model was 0.17 which is less than 50% of that given by Carnot cycle for the no heat recovery mode working at the same operating conditions. The COP predicted by this simulation was 0.4 which was very close to that given by Carnot cycle for the heat recovery mode working at the same operating conditions. The model optimized the adsorption/desorption cycle time of 300 to 400 seconds, switching cycle time of 50 seconds and heat recovery cycle time of 30 seconds. The optimized cycle times maximized both cooling capacity and COP. Also, a parametric study was conducted to optimize the activated carbon mass inside a single bed, the overall heat transfer coefficient for the bed and evaporator and the mass flow rates of all components comprising the chiller. The optimum values increased the COP from 0.35 to 0.5 while the cooling capacity was slightly changed.

نمذجة ومحاكاة مبرد ادمصاصي ذي مرحلتين مبرد بالهواء مع استعادة الحرارة الضائعة

اعداد

فراس محمود رشيد مكاحله

المشرف
الأستاذ ألدكتور علي عبد الحليم بدران

المشرف المشارك
الأستاذ ألدكتور أيمن عدنان المعايطه

ألملخص

تم القيام بعمل دراسة نظريةالمبردالادمصاصي ذي مرحلتين يعمل باستخدام غاز الميثانول والكربون كوسيطي تبريد. مثل هذه الدراسة سوف تساهم في فهم ظروف عمل المبردالادمصاصي ذي مرحلتين وتساهم في انتشاره تجاريا". للاستغناء عن تصنيع المبردالادمصاصي ذي مرحلتين للتمكن من قياس الكفاءة، هناك حاجة لبناء نموذج رياضي يمكنه التنبؤ بذلك.
خلال الدراسة تم بناء نموذجين عدديين باستخدام برمجيات مات لاب هما نموذج يحاكي عمل المبردالادمصاصي ذي مرحلتين من غير الاستفادة من الطاقة الضائعة تارة" بينما النموذج الثاني يحاكي عمل المبردالادمصاصي ذي مرحلتين مع الاستفادة من الطاقة الضائعة. تم مقارنة معامل ألاداء مع النتائج العملية للمبردالادمصاصي ذي مرحلتين للتأكد من نتائج النماذج. تعتمد النماذج على معادلات تفاضلية من الدرجة العاشرة للتنبؤ بدرجات الحراره والتغير الزمني للادمصاص. دلت الدراسة على تطابق نتائج النماذج مع النتائج العملية من حيث معامل ألاداء وقدرة ألتبريد. تم مقارنة الكفاءة نتائج النماذج للمبردالادمصاصي ذي مرحلتين مع معامل معامل ألاداء كارنوت وتبين أنهما متقاربان جدا". استطاع النموذج اختيار أفضل ألأوقات التي تعطي اقصى معامل ألاداء وأقصى طاقة تبريد (300 ثانية خلال دورة التشغيل، 50 ثانية خلال دورة التغيير، 30 ثانية خلال دورة استعادة الحراره) بحيث ترفع معامل ألاداء الى 0.5. هذه المعلومات يمكن تعميمها على مصنعي المبردالادمصاصي ذي ألمرحلتين.

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sat saturation

Symbols:

Symbol	Description	Unit
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Faculty of Graduate Studies

The University of Jordan,

March, 2014

نموذج ترخيص

أنا الطالب : فراس محمود رشيد مقاطعة أمنح الجامعة الأردنية و/ أو من تفوضه ترخيصاً غير حصري دون مقابل بنشر و / أو استعمال و / أو استغلال و / أو ترجمة و / أو تصوير و / أو إعادة إنتاج بأي طريقة كانت سواء ورقية و / أو إلكترونية أو غير ذلك رسالة الماجستير / الدكتوراه المقدمة من قبلي وعنوانها.

Modeling and simulation of a two stage air cooled adsorption chiller with heat recovery

وذلك لغايات البحث العلمي و / أو التبادل مع المؤسسات التعليمية والجامعات و / أو لأي غاية أخرى تراها الجامعة الأردنية مناسبة، وأمنح الجامعة الحق بالترخيص للغير بجميع أو بعض ما رخصته لها.

اسم الطالب: فراس محمود رشيد مقاطعة

التوقيع:

التاريخ: ٢٠١٤/٣/١٢

This Thesis/Dissertation (Modeling and Simulation of a Two-Stage Air Cooled Adsorption Chiller with Heat Recovery) was successfully defended and approved on 2/3/2014.

Examination Committee

Prof. Ali Abdel Al-Halim Badran (Supervisior) ....
Prof. of Mechanical Engineering

Prof. Ayman Adnan Al-Maaitah (Co-Supervisior) ....
Prof. of Mechanical Engineering
Mu'tah University

Prof. Mohammad Ahmad Hamdan ....
Prof. of Mechanical Engineering

Prof. Mahmoud Ahmad Hammad 09/03/2014
Prof. of Mechanical Engineering

Prof. Mohammad Ahmad Al-Saad ....
Prof. of Mechanical Engineering
External Examiner (Private Sector)

DEDECATION

The author dedicates this thesis to the souls of his father, grandfathers and grandmothers.

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The author wishes to express his greatest thanks to his supervisor Prof. Ali Badran and co-supervisor Prof. Ayman Al-Maaitah for their great guidance during the whole study. I am forever indebted to them.

I also extend my sincere appreciation to Professor Ayman Al-Maaitah to give me this chance to work on his own patent which is very honorable to my career. Great appreciation to Prof. Mohammad Al-Saeed, Prof. Mohammad Hamdan and Prof. Mahmoud Hammad for their valuable comments and corrections during Defense session.

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A theoretical study was developed for a two-stage adsorption chiller with an activated carbon/methanol pair. The objective of this work was to model the performance of such chiller and to compare it with the experimental work done by others. Such study will contribute to understand the working conditions of such chiller and lead to popularity of this chiller commercially. However, to design for larger capacity and to conduct a pre-operation detailed test, a simulation and modeling of such chiller needs to be conducted. No such studies have been done for this chiller so far so the need for larger capacity chillers and testing for various weather conditions still remains. As such, further work is necessary to establish theoretical model of this chiller so that capacity and performance could be easily predicted.

In this work, the following models were conducted numerically using MATLAB: modeling and simulation of the performance of two-stage adsorption chiller with and without heat recovery and then the models were validated by making comparison of the performance with experimental data for the two-stage adsorption chiller. The model was based on 10^{th} order differential equations; six of them were used to predict bed, evaporator and condenser temperatures while the other four equations were used to calculate adsorption isotherm and adsorption kinetics. This chiller is new patent chiller so the models results validated only with experimental data since no such model was built for the two stage air cooled adsorption chiller.

It was found that the simulation model results for the two stage air cooled chiller agreed well with experimental data in terms of cooling capacity (6.7 kW for the model against 6.14 kW for the experimental result at 30 °C cooling water temperature). The COP predicted by this model was 0.17 which is less than 50% of that given by Carnot cycle for the no heat recovery mode working at the same operating conditions. The COP predicted by this simulation was 0.4 which was very close to that given by Carnot cycle for the heat recovery mode working at the same operating conditions. The model optimized the adsorption/desorption cycle time of 300 to 400 seconds, switching cycle time of 50 seconds and heat recovery cycle time of 30 seconds. The optimized cycle times maximized both cooling capacity and COP. Also, a parametric study was conducted to optimize the activated carbon mass inside a single bed, the overall heat transfer coefficient for the bed and evaporator and the mass flow rates of all components comprising the chiller. The optimum values increased the COP from 0.35 to 0.5 while the cooling capacity was slightly changed.

Chapter One

Introduction

1.1 Background

With growth in people life standards, the demand for Heating, Ventilation and Air Conditioning (HVAC) and industrial cooling has increased and consequently the electrical consumption. Common practice indicates that 50% of electricity consumption in Jordan goes for air conditioning. To reduce the electricity bill, solar based power generation should be adapted. One alternative is Photovoltaic (PV) with expensive storage and low efficiencies. Other alternative is to use solar heat source for cooling by using adsorption chiller. The adsorption chiller is a promising candidate to utilize solar or waste heat at situations near environmental temperatures. Adsorption chillers were widely studied by many researchers due to many advantages over compression and absorption chillers. Some advantages were lower grade heat source, silent, possibility for storage, simple control and maintenance and finally environment friendly chiller with zero ozone depletion potential and low potential for global warming. However, adsorption chillers had some disadvantages such as low Coefficient of Performance (COP), larger volume and weight and more expensive when compared with vapor compression chillers. A lot of research was conducted to improve COP by introducing new thermal cycles or new working pairs which increase the complexity of the adsorption chiller. Most available adsorption chillers use one stage non-regenerative cycle that operates at temperature higher than 90°C which requires either high temperature fossil fuel collector, vacuum tube solar system or large scale Concentrated Solar Power (CSP). This equipment contributes to high initial cost of the cooling systems and the problems associated with steam. A new two stage adsorption chiller was patented in USA and Europe, built and tested for small scale capacity around 7 kW with promising results. The new chiller uses two stages (Desorption/Adsorption) beds that make it possible to run the chiller at high ambient temperature ranges up to 50 °C and hot water temperature as low as 60 ºC and produces chilled water as low as 7 ºC. This high ambient application is important since no water consuming cooling towers is needed. This application is essential for locations that are poor in water (such as Jordan) or for humid climates where wet cooling towers will not work properly (humid Gulf areas).

A major advantage of the new chiller is that it is regenerative, which enables the operation of the chiller while regeneration is continuing, although intermittently. Another advantage over the conventional chiller is the use of air to cool down the condenser instead of water.

The new chiller is very important to Jordan and countries of similar climate in addition to hot humid climates such as Gulf countries due to the use of available solar heat all around the year with no impact on water resources or the need for evaporative cooling.

1.2 Overview of Adsorption Cooling Systems

The adsorption chiller is a thermally-powered cooling system in which the term "adsorption" refers to solid physical sorption. In an adsorption cooling cycle (or heat pump), the mechanical compressor in vapor-compression cycle powered by electricity is replaced with a "thermal compressor" that is driven by low grade thermal energy such as solar energy or waste heat.

1.3 Research Hypothesis

Although there had been many theoretical studies on multistage adsorption chiller, no studies has been conducted for a working chiller at Mu'tah University since 2012. Such studies contribute to understand the working conditions of such chiller and lead to popularity of the chiller commercially.

The two stage air cooled adsorption chiller was built at Mu'tah University under the supervision of Al-Maaitah. However, to design for larger capacity and to conduct a pre-operation detailed test, a simulation and modeling of such chiller needs to be conducted. No such studies have been done for this patented chiller so far.

The need for larger capacity chillers and testing for various weather conditions still remains. As such, further work is necessary to establish theoretical model of this chiller so that capacity and performance of the chiller could be easily predicted.

1.4 Aims of the Study:

In this work, the following will be conducted:

1. Modeling and simulation of the performance of 8 kW, two-stage adsorption chiller without heat recovery.
2. Modeling the performance of 8 kW, two-stage adsorption chiller with heat recovery.
3. Comparison of the above models.
4. Transient modeling of a two-stage chiller.
5. Comparison of the performance with experimental data for the two-stage adsorption chiller.
6. Preliminary design for 16 kW chiller.

1.5 Organization of the Thesis:

Thesis is composed of six chapters:

The first of which is introduction and background for adsorption chiller.

Chapter two is about literature review for adsorption cycles, properties of activated carbon and methanol pairs, adsorption equilibrium and adsorption equations. Chapter three incorporates the theory for adsorption cycles, properties of activated carbon and methanol pairs, adsorption equilibrium and adsorption equations.

Chapter four illustrates the mathematical model to simulate chiller performance. Chapter five covers the results and discussion of simulation and the validation of the model by experimental work conducted at MU'TAH University by Millennium in 2012. Chapter six covers the conclusions and recommended future work.

Chapter Two

Literature Review

2.1 Introduction:

Since the eighties of last century, many researchers investigated the performance and operation of adsorption in air conditioning, freezing and heat pump applications. The subject was handled experimentally and mathematically from basic fundamentals, number of stages, working pairs, mass and heat recovery, cycle time optimization, in addition to many parametric studies for chiller components like adsorption bed and heat exchangers. Two of the pioneer researchers were (Sakoda and Suzuki, 1983) who carried out many fundamental experiments on the solar-powered adsorption cooling system. A simple model which takes into account both adsorption properties and apparatus characteristics was used to interpret experimental results. The heat and mass transfer was also interpreted by this model. They studied quantitatively the regeneration temperature on the cooling performance.

2.2 Single Stage Adsorption Chiller

Alam,et al.(2004) studied possible design and operating conditions for silica gel-water adsorption refrigeration cycles driven by near ambient temperature waste heat source (45-70) °C. COP was proportional to cycle time and heat transfer coefficient was inversely proportional to cooling water inlet temperature. Cooling capacity was improved by addition of silica gel to the bed.

Chua,et al. (2004) proposed transient distributed parameters model for a two bed, silica gel-water adsorption chiller. They found good agreement between their model and experimental data. They discussed the importance of heat recovery and the effect of extra system piping on the system performance. They also found that the chiller was able to maintain its cooling capacities over a fairly broad range of cycle time.

Miyazaki, et al. (2010) investigated the performance for dual evaporators, three beds for cooling applications. They found that the Spesific Cooling Capacity(SCP) and COP were 1.5 and 1.7 times more than those of single stage, two beds adsorption chiller.

Habib,et al. (2011) investigated the performance of combined adsorption refrigeration cycles. The novel combined cycle amalgamates the activated carbon (AC)-R507A as the bottoming cycle and AC-R134a cycle as the topping cycle and delivered refrigeration load at as low as 10 °C at the bottoming cycle. Results showed that the combined adsorption cycles were feasible even when low-temperature heat source was available.

Ahmed,et al. (2012) presented the key equations necessaryfor developing a novel empirical lumped analytical simulation model for commercial 450 kW two-bed silica gel/water adsorption chiller incorporating mass and heat recovery schemes. The adsorption chiller governing equations were solved using MATLAB. The simulation model predicted the chiller performance within acceptable tolerance and hence it was used as an evaluation and optimization tool. The simulation model was used for investigating the effect of changing fin spacing on chiller performance where changing fin spacing from its design value to mini-mum permissible value increased chiller cooling capacity by 3.0% but decreased the COP by 2.3%. Genetic Algorithm optimization tool was used to determine the optimum cycle time corresponding to maximum cooling capacity, where using the new cycle time increased the chiller cooling capacity by 8.3%.

2.3 Multi-Stage Adsorption Chiller

Saha, et al. (1995) investigated analytically the performance of the thermally driven, advanced three-stage, silica-gel, adsorption chiller utilizing low grade waste heat of 50 ° C and 30 ° C cooling water. They studied the influence of operation conditions like temperatures, flow rates and cycle time on cooling output and COP. The advantage of this chiller was that it was operated at small regeneration temperature lift (heat source-cooling water temperature) than other heat driven chillers. For the proposed, three-stage, adsorption chiller, the temperature lift was between 20 and 30 K.

Teng, et al. (1996) reviewed the fundamentals of adsorption cooling and heat pump systems. They proposed a thermal model based on Dubinin-Radushkevich equation and thermodynamic analysis. They studied variable physical properties with temperature such as specific heat of working pairs and isosteric heat of adsorption. The performance of advanced cycle are analyzed and compared with basic adsorption cycle.

Saha,et al. (2001) proposed design and prototype for two-stage non-regenerative adsorption chiller. The found that the two-stage chiller can be operated efficiently at 55 °C solar/waste heat sources in combination with a 30 ° C coolant temperature.

Cerkvenik,et al. (2001) discussed the influence of main features of adsorption cycles in comparison to absorption cycles. They confirmed that it was mainly the lack of solution of a solution heat exchanger which lowers the adsorption COP and not the physical properties of the working pairs therefore there was still a lot of room to improve solid sorption heat pump.

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