Institut International d'Ingénierie de l'Eau et de l'Environnement
International Institute for Water and Environemental Engineering

SIMULATION AND ANALYSIS OF THE COOLING DEMAND OF A SEMINAR ROOM; INVESTIGATION OF THE USE OF A SOLAR DESICCANT EVAPORATIVE COOLING SYSTEM

PRESENTED FOR THE DEGREE OF ENGINEER OF RURAL EQUIPMENT

Thesis presented and defended on the 2nd of June 2008 by

Jules Voguelin SIMO TALA

Supervisors: Coulibaly YEZOUMA
Prof., Lecturer
UTER GEI, Ouagadougou

Emmanuel W. RAMDE
M., Lecturer
Department of Mechanical Engineering,
KNUST, Kumasi

Members of the Panel:

Chairman: Prof Coulibaly YEZOUMA

Other members:

Mr. Emmanuel W. RAMDE
Dr. Yao AZOUMAH
Mme Susan STRAND

Year group 2007/2008

DEDICATION

This work is the result of years of study, sufferance, joy and pleasure.

I firstly dedicate it to the **Mighty God** who always lightened my way and my life.

LORD MAY YOUR WILL BE!!

Secondly I dedicate it to my family who is for me a source of inspiration and comfort.

HOPE OUR AIM ALMOST REACHED!!

Finally I dedicate this work to all the lecturers of 2iE, all my friends and class mates with whom I have always shared my best and bad moments.

FIND IN THIS A SOURCE OF DETERMINATION, UNITY AND FRIENDSHIP!!

ACKNOWLEDGMENT

This work is the initiative of **Mme Susan Strand**, Lecturer at 2iE. It has been supervised by **Prof Coulibaly YEZOUMA** and **Mr Emmanuel W. RAMDE**.

Madam STRAND, this work done in Kumasi is the pedestal of my English learning and an improvement of my scientifical knowledge. Find in it an expression of all my gratitude

Prof COULIBALY, I use this occasion to address to you all my satisfaction for the precious knowledge I have gotten from you. Receive the expression of all my joy.

Mr. RAMDE, in spite of your dense timetable you found time to listen to me, follow and correct my work. Find in these words an expression of all my happiness.

SUMMARY

The announcement of the depletion of fossil fuels and the impact of the use of refrigerant in conventional vapour compression cycle for air conditioning have brought scientist to think of the sustainable use of energy, the development of new source of energy and the fight against global warming and ozone depletion. In this thesis, an investigation of the use of solar energy for cooling purpose is done through the simulation of the cooling demand of a conference room and the numerical study of a desiccant evaporative cooling system in a tropical humid context. After modelling the building and the desiccant plant with the software TRNSYS, the thermal load are computed with an hourly time step. The results are then compared with the simplified method of loads computation in tropical countries. The computed thermal loads are used to investigate the behaviour of a desiccant cooling system in a tropical humid region of Africa. The results have shown a high regeneration temperature of the system due to the high humidity ratio of the location. The results also indicate a good autonomy of the desiccant cooling system between 10am and 3pm; time between which high insulation is recorded. Also this study has shown the possibility of the use of a storage tank to delay the excess energy of the period of high sunniness for the less sunny hours of the evening.

Key Words :

1 : TRNSYS
2 : Desiccant cooling
3 : Thermal load
4 : Simulation
5: Regeneration

RESUME

L'annonce de l'épuisement de combustibles fossiles et l'impact de l'usage de réfrigérants dans les cycles conventionnels à compression de vapeur pour climatisation a amené les chercheurs à l’introduction des concepts d’utilisation rationnelle de l’énergie, du développement de nouvelles sources d'énergie aussi bien que de la lutte contre le réchauffement de la planète et la destruction de la couche d’ozone. Dans ce travail, une investigation de l'utilisation de l'énergie solaire dans l’optique d’une climatisation active est faite à travers la simulation de la demande frigorifique d'une salle de conférence et une étude numérique d'un cycle dessiccatif à régénération solaire. Après la modélisation de la salle et de l’installation dessicante avec le logiciel TRNSYS, les charges thermiques sont calculées avec un pas de temps horaire, comparées à la méthode simplifiée en pays tropicaux pour le jour de pic et utilisées pour étudier le comportement du cycle dessicatif en climat tropical humide d’Afrique. Les résultats ont montré la forte température de régénération du système dû à la grande humidité relative de l'ambiance et la capacité d'un système autonome à fonctionner de 10 à 15h pendant les heures de pointes solaires pour le pic frigorifique annuel. Aussi est-il mis en évidence la possibilité d’utilisation d’un ballon de stockage pour différer l’excès d’énergie des heures de pointe aux heures de faible ensoleillement de la soirée.

Mots clés :

1 : TRNSYS
2 : Cycle dessicatif
3 : Charge thermique
4 : Simulation
5: Régénération

NOMENCLATURE

COP: Coefficient Of Performance
Cp: calorific capacity
CPC: Compound Parabolic Concentrators Collector
f: fractional variable describing the temperature mixing effects between outlet air and condensate.
F1: Jurinak isopotential equation
F2: Jurinak isopotential equation
$\mathbf{f_{part}}$: fraction of the electric power converted into heat
h: enthalpy
m: mass flow rate
P: Electrical Power
p: pressure
Q: Heat flux
RH: Relative humidity
Q: Heat flux
T: Temperature
TRNSYS: Transient System Simulation Program
w: humidity ratio
δ : Control function
ε : effectiveness

Subscripts

a: air
cond: condensation
conv: convection
cp: coupled
eff: effective
g: gain
i: infiltration
in: inlet
min: minimum
out: outlet
r: radiation
s: surface
w: water
spt: set point

LIST OF TABLES

LIST OF FIGURES

CONTENT

GENERAL INTRODUCTION

Buildings are one of the most important energy consuming sectors in the world. In Europe, they represent 40% of the global energy consumptions where a very high percentage is used to cover the cooling, heating and lighting needs (Dascalaki, Santanousris M. 1991). In sub Saharan Africa countries, 60% of energy consumption in building comes from Air conditioning (IEPF, 2002). The role of an air conditioner is to overcome the thermal loads of a building in order to maintain the desired indoor conditions. Conventional vapour compression air conditioners, most of the cases are actually used for that purpose but their refrigerants generally have the potential of depleting the ozone layer. Moreover, they contribute to global warming. The use of passive cooling as well as solar assisted air conditioning can contribute to a significant reduction of the total electrical energy consumption in buildings; hence reducing global warming and ozone depletion.

The main purpose of this work realized in KNUST, Kumasi, Ghana is to use transient system simulation software TRNSYS to simulate and analyze the cooling demand of a conference room then, investigate the use of a solar desiccant cooling system. It is divided into six sections organized as follow:

After a general introduction, a literature review on solar cooling technologies is presented followed by the objectives, justifications and a complete methodology of the work. Then, a complete modeling of the building and the cooling system is presented followed by a yearly simulation with the software. The results of simulations are presented, analyzed and discussed at the end of this thesis followed by a general conclusion and recommendations.

I- LITERATURE REVIEW

The production of cold is a topic on which researchers have worked for long and are still working to find a way to improve the different processes, taking into account the use of renewable energy. The results of these studies have produced with the course of time broad cooling technologies from commercially available one to those still under experimentation. Solar cooling gains interest from researchers because the cooling demand is generally in phase with the availability of solar radiation and also because these systems produce less global warming gazes. This section presents the ongoing work on different cooling technologies while emphasizing on the use of the solar energy for the expansion of these systems.

1.1- Cooling Systems Technologies

The main purpose of the production of cold is to balance the thermal loads of a domain for many applications. Very wide technologies are use for that purpose notably:

- **The "Peltier Effect"**

The Peltier effect (called also thermoelectric effect) is a physical phenomenon of heat displacement in presence of an electric current. The effect occurs in different nature conductor materials bound by junctions (contacts). One of the junctions gets cold slightly, while the other warms. It is used in space equipment, some electronic equipments cooling, car cooling and sometimes in small refrigerators for food conservation.

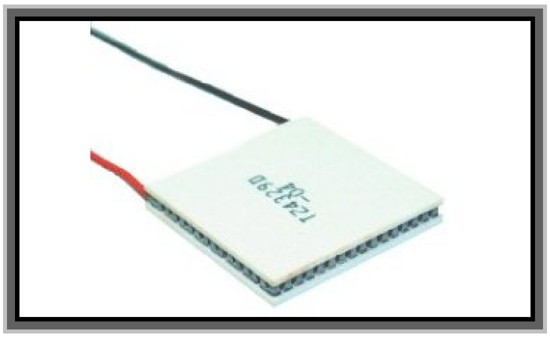


Fig.1: *Single stage Peltier cooler* (http://www.dtkit.it)

- **The magneto-calorific refrigeration**

It uses a statistical thermodynamic principle based on the reorganization of the electronic processing of a body exposed to a strong variable magnetic field. The process is also called adiabatic demagnetization when only a drop in temperature is researched. The magnetocaloric refrigeration system is composed of pumps, electric motors, secondary fluids, heat exchangers of different types, magnets and magnetic materials but the process is at its early stage of development. Continuous improvements are made for the optimization of the cooling cycle. However, due to the low temperature requested for the cooling of the supraconducting magnet, the technology is clearly inappropriate and extremely expensive for building application.

- **The vapor compression cycles**

They use the circulation of a refrigerant through the loop compression-expansion-evaporation-condensation to produce cold. They are basically made of four components namely a compressor, a throttling device, an evaporator and a condenser. The refrigerant undergoes successive processes of vaporization in the evaporator (production of cold space, absorption of heat from a space), condensation in the condenser (releasing of heat to the environment), compression in the compressor (consumption of electricity) and expansion in the throttle. Vapor compression cycles are the most common technology of production of cold, and then are source of high consumption of energy in buildings. Furthermore the energy required for the functioning of these systems is generally produced from fossil primary energy conversion which is source of pollution. A schematic diagram of a vapour compression system is illustrated in **figure2**

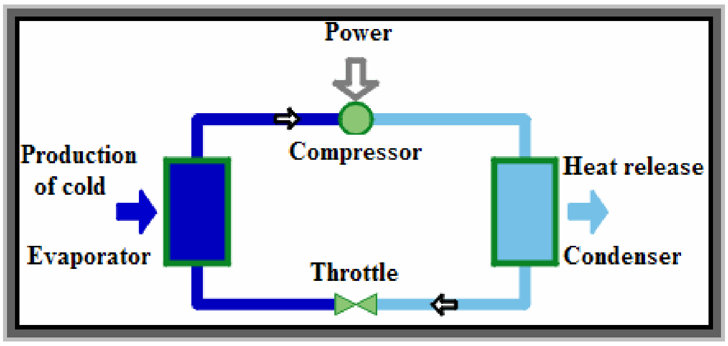


Fig.2: *Classical vapor compression cycle* (http://www.energie.arch.ucl.ac.be)

- **Thermal systems**

In contrast to vapor compression cycles, thermal systems use a thermal energy to produce cold through ab/adsorption cycles. Although they seem different from conventional vapour compression cycles, most of cases they are also made of four components namely a condenser, an ab/adsorber, a regenerator and an evaporator.

Vapor compression cycles and thermal cycles are the most common technologies used in refrigeration and air conditioning. The former uses the electric power for the compression of the refrigerant in the compressor while the latter needs a thermal source for the regeneration of the ab/adsorded refrigerant. The great interest of thermal systems is that they can use waste energy or solar energy.

1.2- Solar Assisted air Cooling technologies

Solar energy can be converted for cooling purpose by two basic ways:

- **Solar photovoltaic**

Here the solar radiation is converted into electricity by photovoltaic panels. Afterwards, the electricity created is used to produce the required cold using vapor compression cycles. This classical way requires the use of refrigerating fluids which are not often environmental friendly. Besides, this way is not always the best as far as concerns the efficiency and the cost of installation of the system.

- **Solar thermal**

Here, the solar radiation is converted into heat by the use of solar thermal collectors. This heat can be used to produce cold in an open or closed cycle through the process of sorption. The main technologies using sorption are absorption chillers, adsorption chillers and desiccant cooling systems. Their description will be made in the following paragraphs.

Another way of producing cold by heat transformation is the thermo mechanical process. In this process the heat produced by solar collectors is used to vaporize water that can be used in a Rankin or steam jet cycle. **Figure3** summarizes the major technologies of production of cold from solar energy

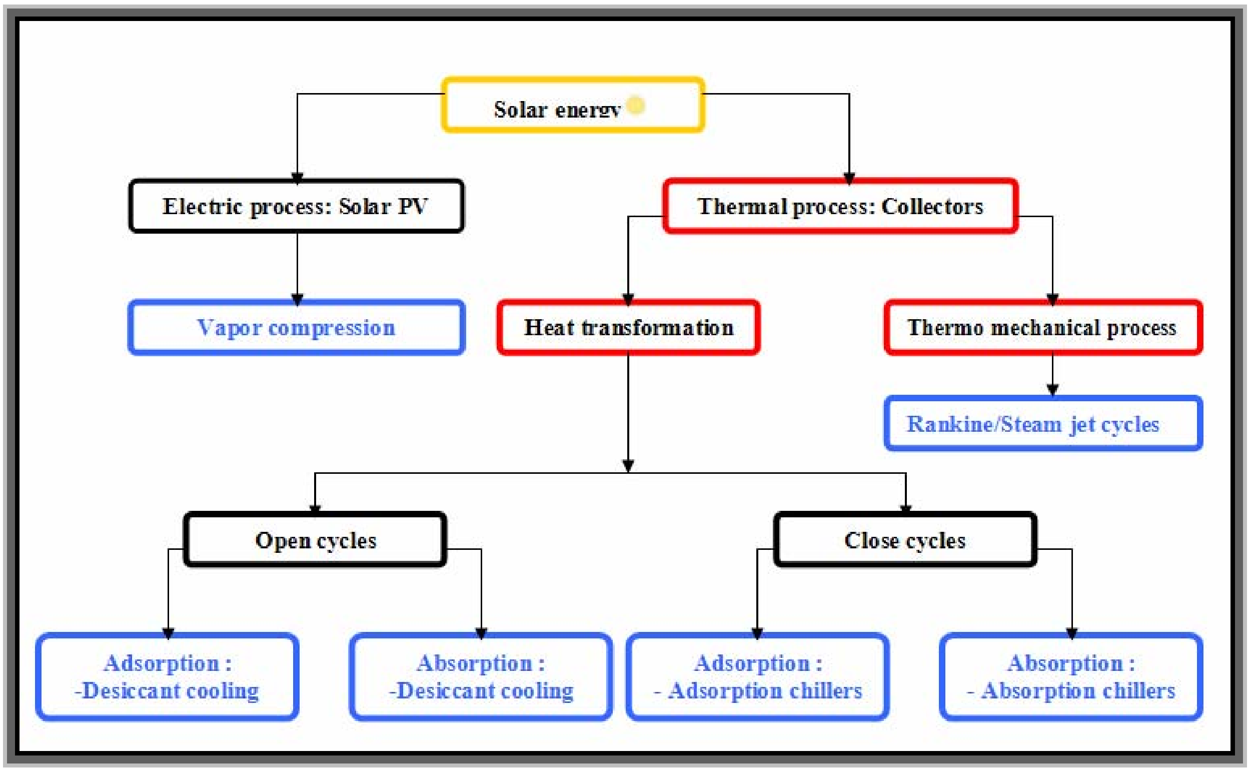


Fig.3: *Different processes of solar cooling technologies* (Henning, H. M. 2003).

1.3- Solar sorption cooling principle

By definition, the sorption is the reversible physical/chemical/physicochemical process in which a particle of fluid is trapped in or on a body. It often happens between gas and solid/liquid. When the particle is only fixed on the body's surface, the process is called adsorption. However, when the particle is trapped in the body, the process is called absorption. Particles trapped are called adsorbate/absorbate and the body sorbent. Absorption generally happens between liquid and gaz. Likewise, adsorption also happens between solid and gas. The releasing of a trapped particle is called desorption and needs a certain quantity of heat. This reversible process is used to produce cold by different ways. The heat needed during the desorption process is generally produced by the conversion of fossil energy in many way. Solar thermal energy which is an infinite and clean energy finds its interest here because it can be simply and properly used to produce the required regeneration heat. Different solar thermal systems nowadays are used for air conditioning.

1.3.1- Absorption chillers

An absorption chiller is made of many components namely, an absorber, an evaporator a condenser and a concentrator/regenerator as represented in **Figure4**. The cooling effect is based on the evaporation of the refrigerant in the evaporator at very low pressure. The vaporised refrigerant is absorbed in the absorber, thereby diluting the absorbent solution. The absorption process efficiency is increased by cooling (heat evacuation). The solution is continuously pumped into the generator, where the regeneration of the solution is achieved by a heating process supplied by a solar collector field.

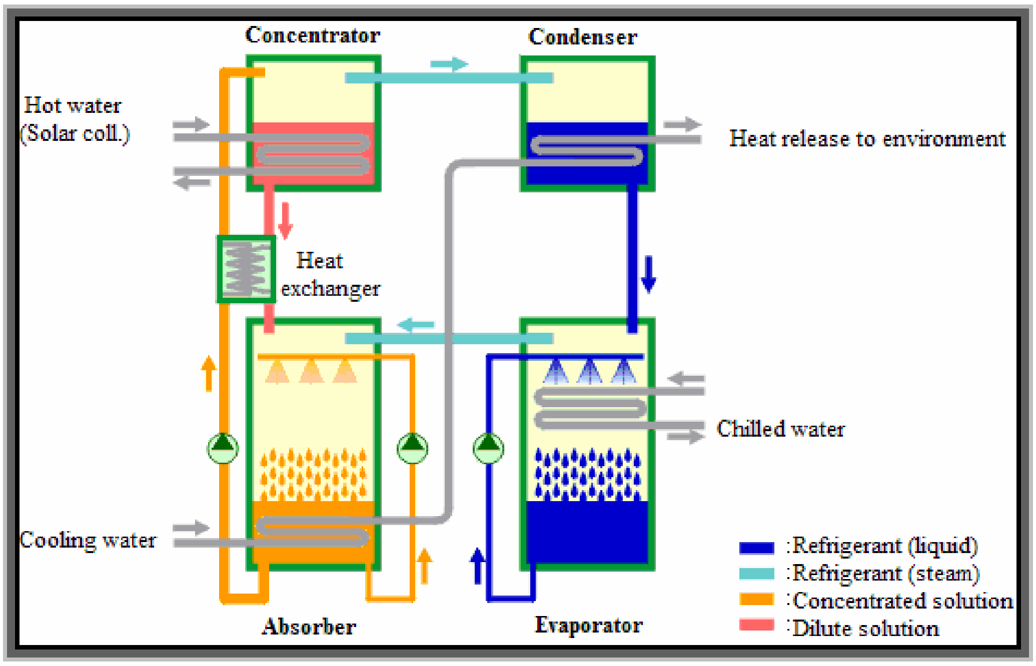


Fig.4: *General principle of an absorption chiller* (http://www.energie.arch.ucl.ac.be).

The refrigerant leaves the generator after this process, condenses through the application of cooling water in the condenser and return into the evaporator for the next cycle. Absorption chillers are the most used chillers throughout the world (ESTIF, 2006). By construction, some operate with a 'single effect' (one stage absorber/concentrator) and some other with a 'double effect' (two stage absorber/concentrator).

1.3.2-Adsorption chillers

Here the adsorbent is a solid body and then cannot flow as an absorbent for the regeneration process. A solution to this problem is the use of two adsorbers which function by turns as adsorber and desorber. Each adsorber accomplishes a cycle. In a first period, the first adsorbent is used for the production of cold while the other is heated (solar assisted) for regeneration. In the second period, when the first adsorbent is saturated, it is replaced by the second for the production of cold and is then itself regenerated.

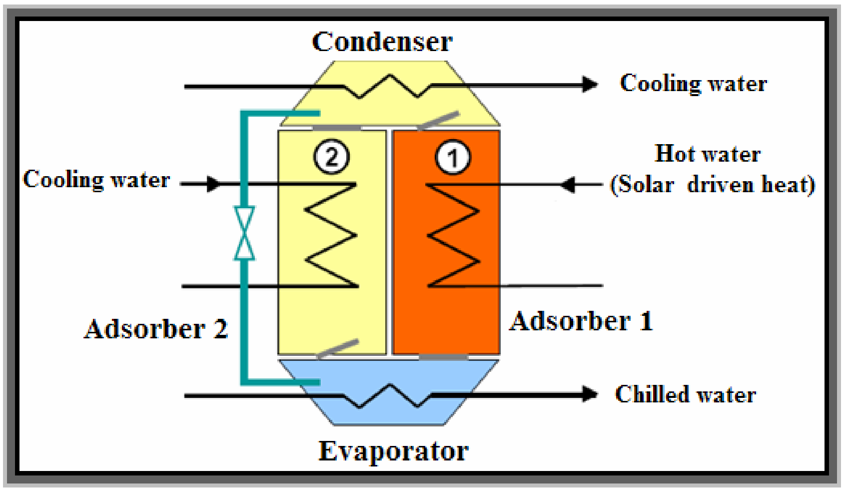


Fig.5: *Description of the general principle of an adsorption chiller* (ESTIF, 2006)

1.3.3- Desiccant cooling

Desiccants cooling are particular types of solar assisted air conditioning that use solid adsorber for the cooling of ambient internal building air following an open cycle principle. In general these systems use a desiccant rotary wheel as adsorbent and function such as described below:

Warm and humid ambient air enters the slowly rotating desiccant wheel and is dehumidified by adsorption of water (see **Figure6**. below). Since the adsorption process is exothermic, a rise in temperature of the dry air is noted. While passing through the heat reclamation rotor, the dry air is pre-cooled indirectly by a heat exchange with the counter-flow air. Afterwards, the air is humidified in a controlled humidifier accordingly to the desired temperature and humidity. This results in a subsequent decrease of temperature of the air before the entry in building.

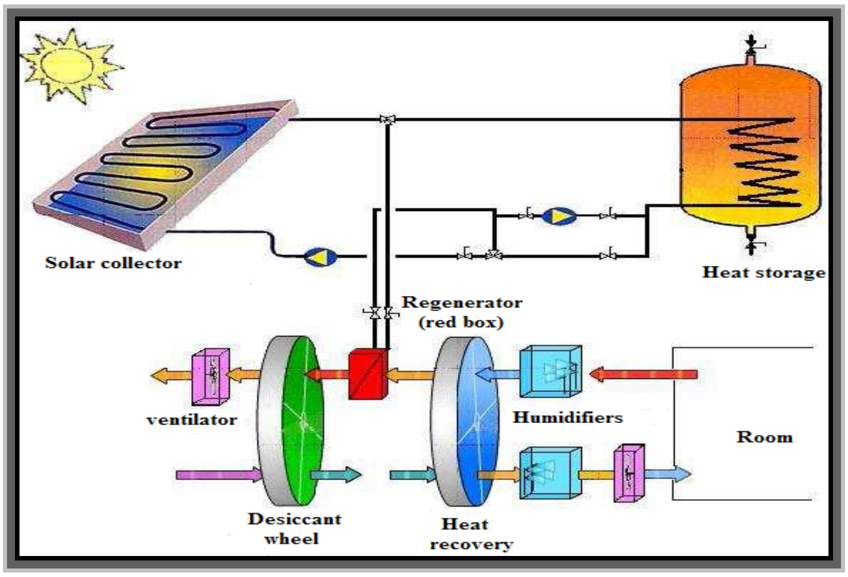


Fig.6: *Different components of a desiccant cooling* (Chadi Maalouf, 2006).

Air becomes stale at the return from the building (thermal building loads). The stale air is hardly humidified in the second humidifier such that to bring its humidity closed to saturation in order to increase it potentiality for cooling. The second passage in the heat reclamation preheats the air by an exchange with the counter-flow air. Then, an external heater (solar thermal energy) supplies the heat needed for the regeneration of the wheel. While passing again through the wheel, the heated air transfers its energy before being pulsed in the nature.

Some other technologies using the adsorption principle are adsorption ice maker refrigerators. They use only one adsorption chamber for ice production but they have a daily cycle due to their direct dependence on the succession between day and night for the production of the useful cold. It is important to notice that cold is produced only during the night. A large number of handly units are intended for the conservation of medicine in rural area of tropical African countries (Djin P., Cherbuin O., Hildbrand C., Mayor J., 2003)

1.3.4- Performance evaluation

Whatever the type of technology for the production of cold by absorption/adsorption, the general principle can be summarized by the following diagram.

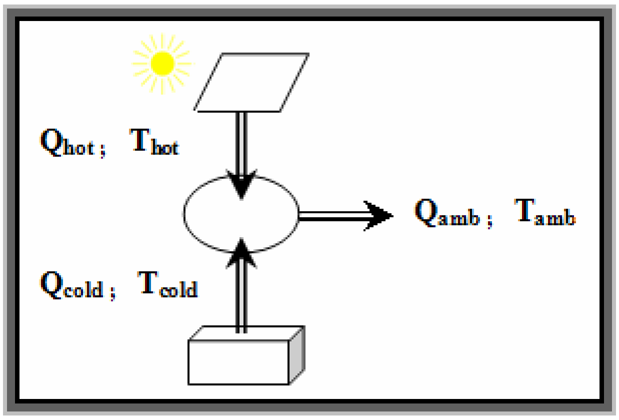


Fig.7: *General model of a solar cooling machine.*

In this diagram, Q_{hot} is the supplied heat by the solar equipment for regeneration, Q_{cold} is the heat removed from the building (useful cold) and Q_{amb} represents the quantity of heat released to the environment. The efficiency of the cooling system is evaluated by a dimensionless number called thermal Coefficient Of Performance COP. By definition it is given by the following relation:

$$COP_{thermal} = \frac{Q_{cold}}{Q_{hot}}$$

It is important to note that this relation does not take into account the quantity of electricity needed by auxiliary equipment like fans and pumps.

Earlier works [Henning, H. M. (2003); Djin P., Cherbuin O., Hildbrand C., Mayor J., (2003) ; Mande S., Ghosh P.; Oertel K., Sprengel U. (2002)] on solar cooling systems show that the COP of these systems is generally less than 1 unless the particular case of the multistage absorption chillers for which this value is close to 1,4. Compare to classical vapour compression, this value is small but, because of the infinite availability of the sun and the friendship of solar thermal systems with the environment, it does not represent a problem to the expansion of this technology. Besides, the type of sorbent used in the system has a great influence on the system performance and its choice has to be done suitably.

1.4- Different Types of sorbent materials

Current sorbents used for the production of cold are divided into two groups according to the process that takes place namely the absorption or the adsorption.

1.4.1- Absorbent

Absorbents consist, basically of dissolution of a salt in a solution called binary solution. In refrigeration, a couple represents an absorbent and a refrigerant. The most used in absorption chillers are Water/Lithium-bromide and Ammonia/Water. The first item of each couple is the refrigerant.

Systems using the water / lithium bromide benefit of the great enthalpy of vaporisation of water and a very low vapour pressure (Good cooling performance, no need of thick pipes for the circulation of the refrigerant). Furthermore, the binary solution is environmental friendly and does not present a danger for humans. It yields great cooling power. However, its cooling temperature is limited by the water freezing point (Pohlmann, 1988).

Systems using the ammonia/water benefit also from the very great enthalpy of vaporisation of ammonia and particularly the capacity to reach very low temperature contrary to the first couple. However the vapour pressure of the refrigerant is very high (necessity of very thick pipes for the circulation of the refrigerant). Furthermore, it is not friendly for human being because of its volatility and toxicity (Pohlmann, 1988).

In general, absorbents consist principally of salts dissolved in water. These hygroscopic salts lower the vapour pressure of water in solution sufficiently to absorb humidity of a medium. Thereby, absorbent as Lithium chloride or Calcium chloride are used in open desiccant systems with liquid sorbent.

1.4.2- Adsorbents

Adsorbent are micro porous solid presenting a very wide surface per unit mass in order to maximise the vapour adsorption capacity (Clausse M., 2003). They are the main component of adsorption chillers and desiccant cooling. Adsorption chillers are very recent technologies compare to absorption chillers. Typical examples of working pairs are water/silica gel, water/zeolite, ammonia/activated carbon or methanol/activated carbon etc... However, only machines using the water/silica gel working pair are currently available on the market (Hu Jing, Excell R.H.B., 1993). Activated carbon is the current adsorbent used in industrial processes because of its good properties namely, the low bounding energy of adsorption/regeneration and the non polarity which reduce the heat used during the regeneration comparing to other adsorbents.

Furthermore, among the intermittent solid adsorption cycles for solar ice-making refrigerators operating in a daily cycle, the charcoal / methanol combination appears to have advantages over other combinations. The advantages include chemical stability, better performance and the relative inexpensive material locally available in developing countries (Hu Jing, Excell R.H.B., 1993). Because of the wide range of sorbent according to the regeneration energy requirement, the solar conversion unit has to be chosen suitably in order to match the type of sorbent to the corresponding heat production.

1.5- Different Types of Solar Collector Systems

The unique thermal way of conversion of solar energy is the use of thermal collector which absorbs the solar radiation and converts it into heat. Basically there are two types of solar thermal collectors. The fundamental difference between them is the fluid used to drive the heat. One uses water as calorific fluid and the other uses air. Thermal collectors used for air conditioning purpose are mainly flat plates collectors, evacuated collectors, Compound Parabolic Concentrators collectors (CPC collectors) and the solar air collectors. Whatever the type of the collector, the maximum efficiency is achieved by the reduction of the different thermal losses and geometrical constructions. The energy loss in thermal collectors is divided into conductive, convective, radiative and optical losses. A dimensionless number (thermal collector efficiency) characterizes the thermal conversion of a collector. It represents the ratio of the useful heat produced over the total incident radiation energy on the collector.

Flat plate collectors are the most common solar collectors and represents about 90% of the market of covered solar collectors (Henning, H. M. 2003). They are mainly used for hot water production in buildings. In temperate climate their efficiency is increased by the use of selective coating (for the reduction of optical loss). Thus they can be used to drive heat to adsorption chillers and desiccant cooling systems, however their use in these processes requires a high selective coating.

Evacuated tube collectors represent just a little part of the worldwide market of thermal collectors but are the most used in China. They are made of evacuated tube with a pressure of about 0,001 Pa and a cylindrical absorber in which flows the calorific fluid. Because of their good thermal conversion efficiency they are also used in many solar assisted systems as adsorption/absorption chillers and desiccant cooling.

Solar air collectors represent a negligible part of the market of thermal collector. They are basically used for residential buildings' heating purpose. Furthermore, they find a large application in industrial thermal driven heat processes and particularly in solar assisted air conditioning.

The price of a type of collector increases with the technology, the application and most of all the efficiency. Thus, flat plate collectors are the most spread because of their fundamental applications and their relatively low cost (Henning, H. M. 2003). The number of collectors used in thermally driven processes depends on the regeneration heat demand which also depends on the thermal load of the building. Thereby, the overall thermal loads of a building have to be well evaluated in order to better calibrate any solar cooling equipment.

1.6- Overview of previous works on solar desiccant cooling systems.

Very large studies on solar desiccant evaporative cooling have been done in earlier studies in Europe an America and many systems have been implemented and are still in test in these countries.

Chadi Maalouf (2006) modelled the different components of a solar desiccant cooling systems. The different model implemented in the simulation tool SPARK showed that the efficiency of the rotary heat recovery wheel is the most influential element on the electric and thermal performances of the system as well as the efficiency of fans that greatly affect the electric consumption of the system.

Techajunta et al (1999) used silica gel as adsorbent and studied its regeneration with a simulated solar energy in which incandescent electric bulbs were used to simulate solar radiation. The regeneration rate was found to be strongly dependent on the solar radiation intensity while its dependence on the air flow rate was found to be weak.

Joudi et al. (2001) studied the yearly efficiency of a solar desiccant system installed in a two floors individual building in Baghdad. The system was used for cooling and heating during summer and winter respectively. Their studies proved that the main parameter for performance control of the solar unit was the air collector area and the one of the cooling unit depended on the efficiency of the heat reclamation rotor, the humidifiers and the regeneration temperature but not the performance of the regeneration wheel.

Dittmar (1997) studied the feasibility of a solar desiccant cooling system for air conditioning of building in Gothenburg (Sweden) and Würzburg (Germany). The system was coupled to one building of 3 floors with 200 m^2 each. The yearly simulations done with TRNSYS have shown that according to the locality 65 to 85% of cooling demand can be provided by the use of the direct and indirect humidification. During the year, desiccant mode was used between 10 and 20% of the time. Calculations showed that 10m^2 per 100m^2 of building with 75 l of storage tank per m^2 of collector area are necessary to have 75% of solar fraction.

Höfker et al. (2001) experimentally followed a desiccant plant with integrated solar air collector located in Stuttgart. Their results show that it is interesting to bypass part of the return air for regeneration (between 20 and 40%) without affecting the rate of dehumidification of the wheel.

HENNING and al. (2001) studied a desiccant cooling system installed in Riesa (Germany) during the Task25 of the International Energy Agency. It is used for air conditioning of a 330 m3 seminar room with an air flow rate of 2700m3/h. This installation includes 20 m2 of solar collector and a storage tank of 2 m3. An experimental control of the installation during the year 1997, concluded on a solar fraction of 76% (the calculated solar fraction by simulations was 81%). The same author asserts that a need of pre-dehumidification for classical desiccant cooling systems is necessary in high humidity regions.

In this chapter, we have presented the ongoing works on solar cooling technologies in general and we have specifically emphasised on the desiccant cooling technology on which we will focus throughout the following chapters. Almost all the desiccant evaporative systems actually in operation or in test are modelled in climatic zones with a relatively low sunniness (mostly in Europe and America). Despite the high regeneration temperature for the desiccant rotary wheel in warm and humid countries, the investigation of its use in a tropical African country is of interest because of the great availability and the high degree of sunniness. In the next chapter, we will use a building software tool to simulate and analyse the cooling demand of a seminar room located in the tropical African warm and humid climate. After analysis, the results will be used to investigate the use of a desiccant cooling system to meet this demand.

II- OBJECTIVES AND METHODOLOGY OF THE STUDY

Introduction

As any scientific work, the achievement of a study is directly dependent on the main purpose and the schedule defined for that. This chapter details the main objectives of the work and the methodology defined for its achievement.

2.1-Objectives and justifications

The use of vapour compression cycles for building air conditioning is a commonly known technology of comfort supply. The building loads are generally calculated on a basis of extreme conditions for a pick month. This sometimes leads sometimes to over-sizing of cooling equipment resulting in a high cost of exploitation. Furthermore, the use of vapour compression systems constitutes a source of global warming. This is because the electricity used by the equipment is sometimes produced from fossil energy fuels which releases non environmental friendly gases such as nitrogen oxide, carbon dioxide, sulphur oxide and fines particles in the atmosphere. In addition to that, previsions show that with the actual rate of fossil fuel consumption (witch are limited natural resources) and the world population which increases, it is important to insist on the sustainable use of energy and the development of new and renewable energies sources like solar energy.

The general objective of this work is to use an approach of building loads calculation based on an hourly time step computations to investigate the use of a solar assisted air conditioning for a conference room in a tropical humid weather context. The specific objectives of this study are divided into three sections:

- Calculate the hourly thermal loads of a Conference Room with the building energy simulation software TRNSYS
- Analyse and compare the results of the simulations. Comparisons are made with the simplified method of loads calculation.
- Use of the thermal load gotten to investigate the use of a Solar Desiccant evaporative cooling system for the thermal comfort of the room.

2.2-Methodology of the study

The simulations done mainly with TRNSYS are divided into two main parts:

- The calculation of the loads is done after modelling the building by the interconnection and the definition of the inputs of all the necessary components in the user interface. The Test Reference Year (TRY) meteorological data is one of the major input data. It gives the annual hourly (8760 time step) meteorological data of the site. The results of the simulation for each time step of the year are saved in a load file for use in investigating the desiccant cooling system.
- For the investigation of the desiccant cooling system, the overall system is modelled in TRNSYS by the connection of the different components of the system followed by the definition of the inputs for each one. The pre-calculated load are loaded by the building component and imposed on the air flow. Simulations are carried out for each time step of the year (8760 time step). The air parameters are saved as output for each component. The supply air temperature and relative humidity are plotted and compared to the building predefined set point. Also, the solar collector optimum area and the thermal and electrical COP are computed in order to conclude on the feasibility of the system in the chosen climate. More details on the modelling and simulation of the system are presented in the following chapters.

Conclusion

The main purpose of this chapter was to specify and justify the objectives of this work and to state the methodology used in the study. A detailed objectives and an overview of the methodology of the study have been given. In the next chapter, more detail about the software structure, the mathematical model of the building simulation, the building structure and the inputs of each component of the system will be given.

III- MODELLING AND SIMULATION

3.1- Presentation of the Software TRNSYS

TRNSYS is a flexible tool designed to simulate the energy performances of dynamic systems. Developed by the University of Wisconsin and the University of the Colorado in the USA, TRNSYS was initially used to simulate some components relative to the solar energy use. The specificity of the software consists in its modular aspect. Indeed, it is built from a list of subroutines written in FORTRAN. Each subroutine models one module or type. Every type is an independent computer object. It corresponds to an element of the thermal system composed of inputs, outputs and parameters. To simulate a complete system for instance a desiccant cooling system, the user must define the different components of this system first from a library of types and connect them together in order to constitute the complete system. A graphic interface called Simulation Studio allows visualizing all components of the system. The particularity of TRNSYS amongst the others (James P. Waltz, P.E, C.E.M 2000) building simulation tools is its huge library of component witch makes of it one of the most powerful, flexible but less friendly (because of its necessary long learning time) building energy tool.

In the following lines, the above-mentioned software will be used to compute the hourly thermal loads of a local building. Afterwards, the results of this simulation will be used to study a solar assisted desiccant cooling system for air conditioning purpose.

3.2- Building modeling

3.2.1-Geographical description.

The building used for our simulation is the Conference Room located in the Mechanical Engineering Department of the Kwame N'krumah University of Science and Technology, KNUST. KNUST is located in Kumasi, a southern and second main city of Ghana. Ghana is a tropical western African country with a warm and humid climate which becomes progressively dry while moving from the southern to the northern regions. The monthly ambient air temperature is quite stable during the whole year for the southern regions (Kumasi, Accra) with a monthly mean around 29.2°C for the hottest month in Accra. Furthermore, the monthly relative humidity is above 73% for the whole year in Accra.

3.2.2-Building description

The building is a four floor building with the main façade directed mainly towards the North and slightly towards the West. The Conference Room is located at the second floor. It shares a wall with an office respectively at the west and the East. The roof and ground walls are also adjacent to offices. The conference Room is built as follow:

- The walls are made from the indoor to the outdoor of four layers namely, insulation made of wood, plaster, mortar bloc and another plaster. The roof and the floor are slabs made of concrete and plaster. The floor of the room is covered by a carpet.
- The northern and southern walls have the same proportion of glazing and are external walls. The eastern and western walls are adjacent walls and then don't have any window.
- The roof has four double tube lamps and two fans.
- The Conference Room has a maximum capacity of twenty-six seats for daily meetings.
- Each glazing is covered inside by a movable shading device made of curtains. At the out side of each glazing the slab's extensions play a fixed shading device role in order to avoid the direct sunlight on walls and glazing.

3.2.3-Meteorological data and loads calculation

3.2.3-1. Hypothesis and assumptions

Any building energy simulation with TRNSYS requires an interaction between the hourly meteorological data and the building thermal behavior. In order to model our building, some assumptions have been made.

- The weather data used for the simulation is the one of Accra. Indeed, TRNSYS requires a specific weather data format which is usually produced by commercial software such as the METEONORM. With the trial version of that software, we were able to produce just the weather data of Accra. The weather file contains hourly data such as insulation (global and direct solar radiation), ambient temperature, pressure, relative humidity and finally the hourly values of the wind speed. Consequently we assume that the building is located in Accra.
- The boundary walls are adjacent to offices. Some offices are air-conditioned but not all. We use the worst scenario by assuming that all the adjacent rooms are not air-conditioned in order to have the maximum loads. Consequently, we assume that the adjacent wall of the conference room have an imposed external temperature depending on the ambient temperature.

➢ The conference room is used just for workdays. It has a maximum capacity of 26 places. Furthermore, the cooling system that we studied will operate daily according to the availability of the sun. Consequently, we assumed that 20 people can potentially use the room every workday from 8am to 6pm.

3.2.3.2.Load calculation

a- Mathematical formulation

TRNSYS uses the meteorological data, the geometrical data and the set point control to do an energy balance (sensible and latent) in order to compute the hourly latent and sensible load of a building. In a multi zone building, each room represents a thermal zone and the interaction between all the thermal zones are taken into consideration. The following equations are solved with an hourly time step for each zone:

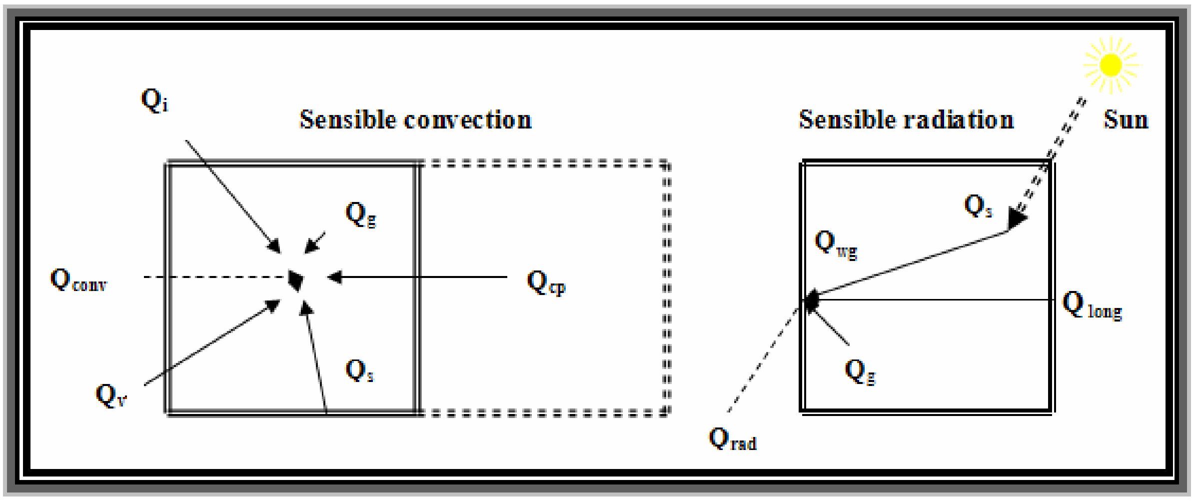


Fig.8: *Building energy balance (Convection in a zone: Left; Radiation on a wall: Right)*

- Sensible convective energy balance (for a zone node)

$$Q_{conv} = Q_i + Q_g + Q_s + Q_v + Q_{cp}$$

For this equation we have:

Q_i : Flux gained by infiltration of external air

Q_g : Flux gained by internal sources

Q_s : Flux gained from an active wall (heated or cooled)

Q_v : Flux gained by ventilation of the zone

Q_{cp} : Flux gained by an eventual air flowing from an adjacent zone.

Q_{conv} : Net convective flux of the zone

- Sensible radiative energy balance (on each zone wall)

$$Q_{rad} = Q_g + Q_s + Q_{long} + Q_{wg}$$

For this equation we have:

Q_g : Flux gained by internal radiative sources

Q_s : Flux gained by the wall from the sun through glazing

Q_{long} : Flux gained by radiation from the other walls and window of the zone

Q_{wg} : Eventual radiative flux flowing toward toward the wall (user define)

Q_{rad} : Net radiative flux at the wall

- Latent energy balance (effective capacity humidity model)

$$m_{eff}\frac{d\omega}{dt} = \dot{m}_i(\omega_a - \omega) + \dot{m}_v(\omega_v - \omega) + \dot{m}_{cp}(\omega_{cp} - \omega) + \dot{m}_g\omega_g$$

For this equation we have:

$\dot{m}_i(\omega_a - \omega)$: Rate at which moisture is added to the zone from the infiltrated air

$\dot{m}_v(\omega_v - \omega)$: Rate at which moisture is added to the zone from ventilated air

$\dot{m}_{cp}(\omega_{cp} - \omega)$: Rate at which moisture is added to the zone from an adjacent zone

$\dot{m}_g\omega_g$: Rate at which moisture is added to the zone by internal source.

$m_{eff}\frac{d\omega}{dt}$: Effective moisture capacitance rate of the zone

b- Modeling with TRNSYS

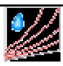
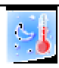
According to the building structure, the infiltration and ventilation air change norm, the following table summarizes the inputs used for our simulation.

Tab.1: *Input data and building structure*

Building dimensions				
High (m)	Width (m)	Depth (m)	Volume (m3)	Orientation (°)
3.04	**5.85**	**7.03**	**125.5**	**11° N-E**
Structure of walls (outside to inside)				
Walls and thickness	Layers			
North and South	*plaster*	*brick*	*plaster*	
Thickness (cm)	1.5	15	1.5	
East and West	*plaster*	*brick*	*plaster*	*wood*
Thickness (cm)	1.5	10	1.5	1
Roof	*carpet*	*plaster*	*concrete*	*plaster*
Thickness (cm)	0.5	1.5	12	1.5
Ground	*plaster*	*concrete*	*plaster*	*carpet*
Thickness (cm)	1.5	12	1.5	0.5
Proportion of window per wall				
Walls	*North and South*	*East and West*	*Roof*	*Ground*
Prop (%)	65 each one	0	0	0
Type of glazing	Simple (louvers)	-	-	-
Set point for cooling and dehumidification				
Cooling temperature (°C)		26		
Dehumidification relative humidity (%)		50		
Internal gains (people) (ISO 7730)				
Number of persons	latent (W)	Sensible (W)	Status	
20	55x20= 1100	65x20= 1300	Seated slightly work	
Internal gains (light and computers)				
Number	Power of each (w)		Type	
8	40		Fluorescent tube	
10	65		Lap top	
Ventilation and infiltration rate (Henning H. M., 2003)				
Ventilation type	Air change flow rate per person		total	
Mechanical	30		**600m3/h**	**4.8Vol/h**
Infiltration type	Air change flow rate per person		total	
Leakage	-		**62.5m3/h**	**0.5Vol/h**

In order to model the building, specific TRNSYS components have to be connected together. Each component represents an independent subroutine of the main program with a specific proforma (structure of input and output, description of the model and variables). Each line of the connection network contains specific input/output defined according to the simulation. The outputs of a component are used as inputs for the following component. The following table summarizes the different components used for the load simulation and their numerical role.

Tab.2: *Component used for building modeling*

Component	Icon	Code	Role
Weather processor	 Weather data	Type 109TMY2	Weather data reader (rectangular time interval), solar radiation on tiled surface and incidence angle processor
Psychometer	 Psychrometrics	Type 33e.bm	Psychometric air parameters calculator from two known (dry bulb temperature and relative humidity)
Sky temperature	 Sky temp	Type 69b.bm	Effective sky temperature calculator (long-wave radiation exchange between external surfaces and atmosphere).
Wing walls	 WingWall S	Type 34bm	Solar radiation on a vertical receiver shaded by an overhang and/or wing wall calculator.
Printer/plotter	 Type65a	Type 65a	The online graphics component is used to display selected system variables while the simulation is progressing.
Equation	 Radiation	No code	Equation manager
Building processor	 Building	Type 65a.bm	This component models the thermal behavior of a building having up to 25 thermal zones.

The schedule of occupation of the room (**see Figure9**.) and related internal energy gain calculator are integrated in the building load calculation.

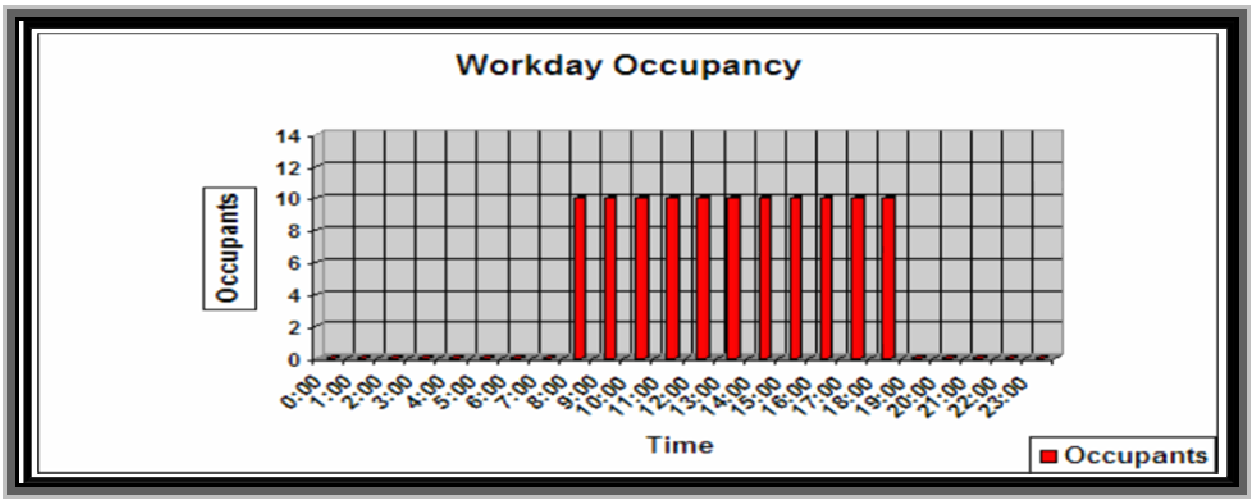


Fig. 9: *Schedule of occupation*

Figure10 represents the entire building model in TRNSYS with all the input/output connection lines. The direction of the arrow on each line indicates the flux direction of outputs from one component to the following. The outputs of a component are used as input for the next component.

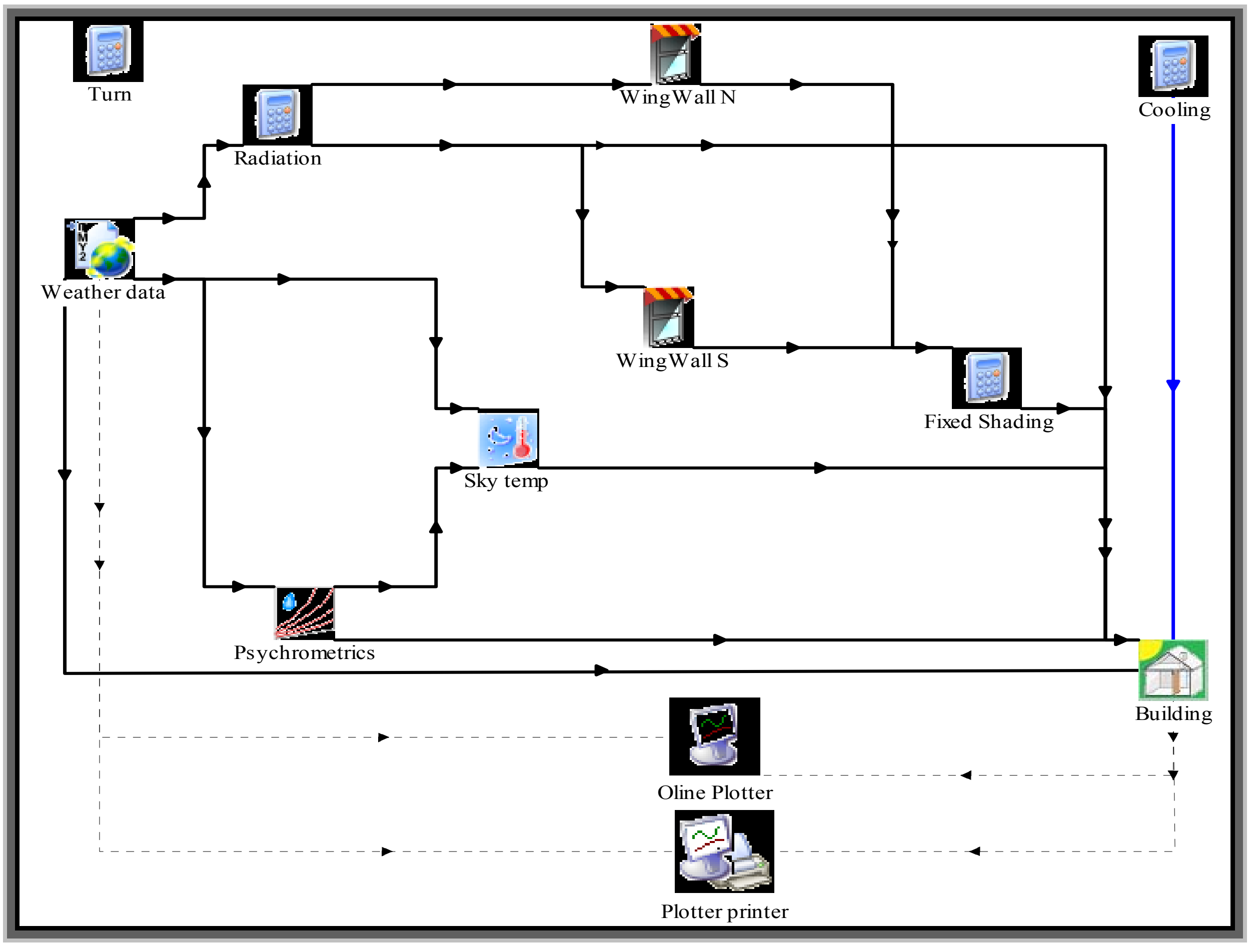


Fig.10: *Overall modeling of the building for load simulation*

3.3- Desiccant Evaporative Cooling system modeling

After the building modeling and load calculation in TRNSYS we present in this section an overview of the mathematical model of all the component of the solar desiccant evaporative cooling plant.

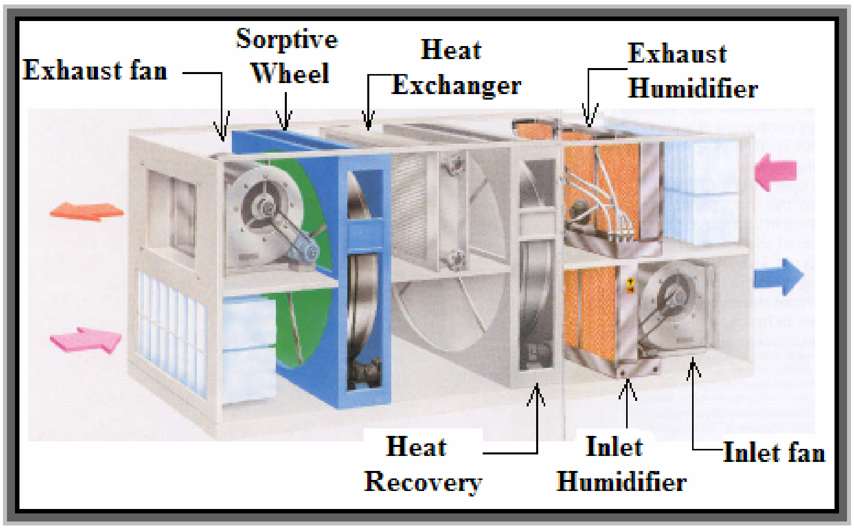


Fig.11: *Desiccant plant handly unit*

3.3.1- Mathematical summery of component's model

3.3.1.1- Fan and pump

The fans are used for the circulation of air in the plant and the pump for the circulation of hot water in the solar unit. TRNSYS models a fan by calculating the outlet air temperature, flow rate and the power consumption according to the control function as follow:

$$T_{out} = T_{in} + \frac{P f_{part}}{\dot{m} c_p} \quad \text{where} \quad \dot{m} = \delta \dot{m}_{max} \quad \text{and} \quad P = \delta P_{max}$$

f_{part} and δ are respectively the fan power fraction converted into heat and the control function. The control function is an input that characterizes the operation status of a component (ON or OFF) according to a predefined schedule. The pump is modeled identically.

3.3.1.2- Simple Adiabatic Humidifier

The humidifiers are used to humidify the air in order to induce a drop in temperature and a rise in humidity ratio.

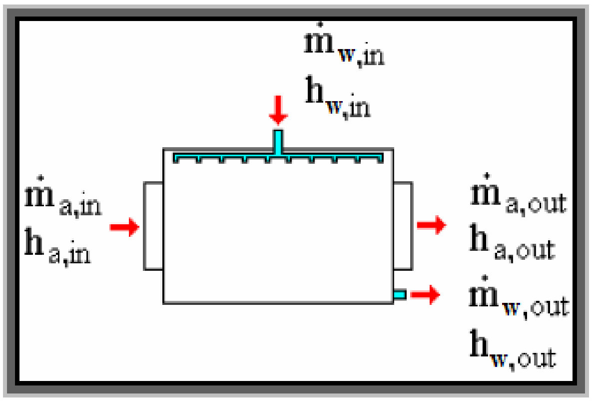


Fig.12: *Simple adiabatic humidifier*

Knowing the inlet air and water parameters, the outlet air or eventually water parameters are computed with the use of the energy balance. TRNSYS use the psychometric subroutine and alternatively (depending on the potentiality of air to completely absorb or not the available water) the following equations to determine the outlet air status.

$$h_{a,out} = h_{a,in} + \frac{\dot{m}_{w,in}}{\dot{m}_a} h_{w,in}$$

$$h_{a,out} = h_{a,in} + \frac{\dot{m}_{w,in}}{\dot{m}_a} h_{w,in} - \frac{\dot{m}_{w,out}}{\dot{m}_a} h_{w,out}$$

$$T_{w,out} = (1-f)T_{w,in} + fT_{a,out}$$

f is a fractional variable describing the temperature mixing effects between outlet air and condensate.

3.3.1.3- Heat recovery

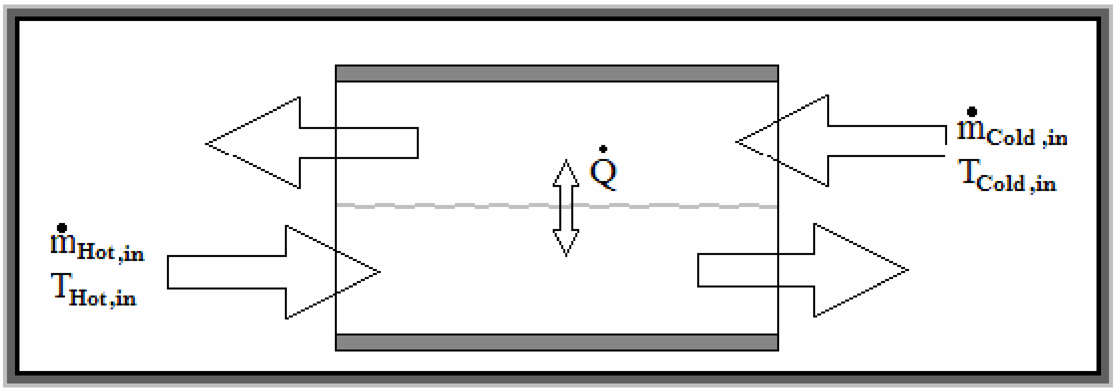


Fig.13: *Sensible heat recovery*

The heat recovery allows the sensible heat transfer from hot air exiting the sorptive wheel and the cold air exiting the exit of the humidifier. It is modeled as a sensible heat exchanger with a possible condensation for both air streams. Knowing the parameters of the inlet air and the sensible efficiency of the component, the outlets parameters are gotten through an energy balance with the call of the psychometric subroutine as follow:

$$C_{min} = MIN(\dot{m}_{cold} Cp_{cold} ; \dot{m}_{hot} Cp_{hot})$$

$$\dot{Q} = \varepsilon_{sens} C_{min} \left(T_{hot,in} - T_{cold,in}\right)$$

$$h_{hot,out} = h_{hot,in} - \frac{\dot{Q}}{\dot{m}_{hot}}$$

$$h_{cold,out} = h_{cold,in} + \frac{\dot{Q}}{\dot{m}_{cold}}$$

$$p_{hot,out} = p_{hot,in} - \Delta p_{hot}$$

$$p_{cold,out} = p_{cold,in} - \Delta p_{cold}$$

In case of condensation during the process, the following relations are used to assess the condensate flow rate:

$$\dot{m}_{hot,cond} = \dot{m}_{hot} (\omega_{hot,in} - \omega_{hot,out})$$

$$\dot{m}_{fresh,cond} = \dot{m}_{fresh} (\omega_{fresh,in} - \omega_{fresh,out})$$

3.3.1.4- Sorptive rotary wheel

The main role of the sorptive wheel is to fix water vapor particles in order to dehumidify the process air entering into the building.

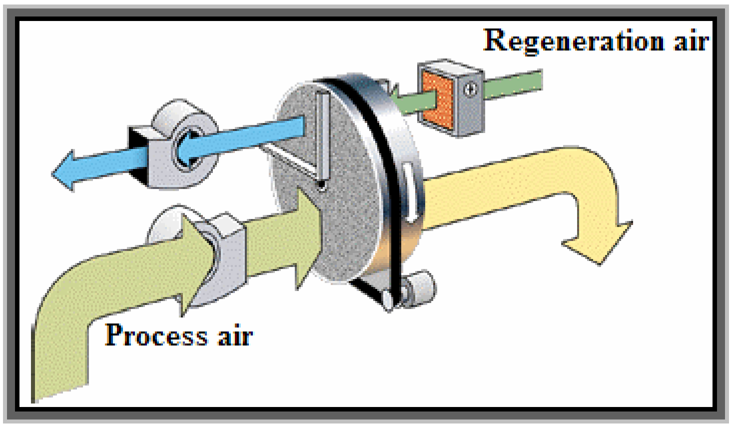


Fig.14: *Sorptive rotary wheel*

Knowing the inlet process air temperature and humidity ratio, the inlet regeneration and outlet process air humidity ratio, TRNSYS determines the regeneration air stream temperature required to meet the outlet humidity ratio set point using an iterative process and the following isopotential equations derived by Jurinak, J.J., (1982) for a silica gel sorbent:

$$F_1 = -\frac{2865}{T^{1.490}} + 4.344\omega^{0.8624}$$

$$F_2 = \frac{T^{1.490}}{6360} - 1.127\omega^{0.07969}$$

The above parameters are determined for an ideal isenthalpic adsorption and regeneration process. In order to take into account the non idealities of the processes, the F1 and F2 isopotentials are further modified by the use of two effectiveness values ε1 and ε2 proposed by Banks (Schultz, K.J., 1983). The speed at which the wheel is designed to turn in a rotary system is adjusted in order to maintain the outlet conditions (6 to 12 rotations per hour (F. E. Nia et al, 2006))

3.3.2- TRNSYS modelling

In order to model the equipment with TRNSYS, the above components are connected each to other according to the design order. Then, the unit is coupled to the solar unit trough a heat exchanger on one side and to the building on the other side. The pre-calculated building loads are saved in a loads file. This data separated into sensible and latent loads are used as input for the building. They are read by another component (data reader) at each time step. The building component is a TRNSYS type witch imposes loads on a flow stream and according to the air flow status determines the return air flow with its thermodynamic properties and the part of loads overcome. The positive sensible loads tend to increase the air temperature at the building exit and the positive latent loads tend to increase the humidity ratio. At each time step, the thermodynamic properties of the air flow are computed through the call of the psychometric subroutines. **Table3** and **Figure14** summarise the inputs parameter of each component and the complete equipment modelling. The blue bold lines represent the process air entering the building and the red bold line the return air stream (stale air).

Tab.3: *Component inputs for the Desiccant cooling simulation*

	Humidifier 1	**Humidifier 2**	**S. wheel**	**Heat rec.**	**Fans**	**Collector**
Parameter /value	P:94kJ/hr	P: 360kJ/hr	P: 500kJ/hr	P: 670kJ/hr	P: 500kJ/hr	Slope: 6° South
	m_w: 2.6kg/hr	m_w: 10kg/hr	HRspt: 0.008	Δp: 0.0009atm	CC: 0.05	a_0: 0.85
	m_a:1800kg/hr	m_a:1800kg/hr	m_a:1800kg/hr	m_a:1800kg/hr	m_a:1800kg/hr	a_1: 13kJ/hr.K.m²
	T_w: 26°C	T_w: 26°C	F1: 0.08	ε: 0.9	p: 1000pa	a_2: 0.05kJ/hr.K².m²
	Δp: 0.0009atm	Δp: 0.0009atm	F2: 0.95			b_0: 0.2; b_1: 0

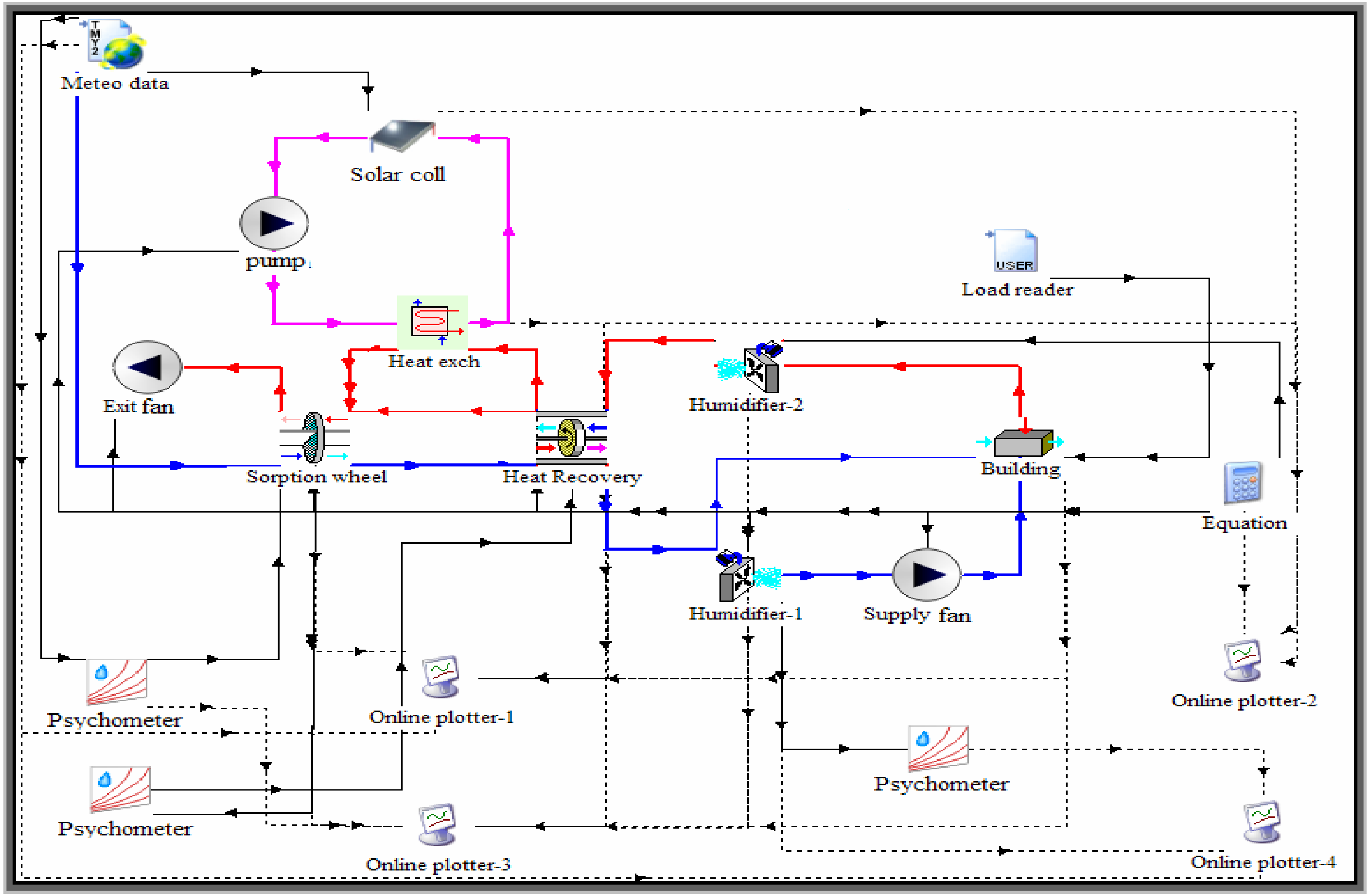


Fig.15: Overall Desiccant cooling system modeling and component connection in TRNSYS

IV- RESULTS, ANALYSIS AND DISCUSSIONS

Introduction

In the previous chapter, we have presented the numerical tool used for the present simulation. Then, we have presented a step by step modeling of the necessary components for the calculation of the thermal loads and the investigation of the desiccant cooling system. In this chapter, we present, analyze and discuss the results of our simulation. Due to the large numbers of data to be treated, we focus for the load calculation on the pick month and particularly on the pick day.

4.1- Building loads, room air status simulation, analysis and discussion

4.1.1- Monthly simulation

Simulations for the loads calculation have been carried out for the overall year. For each time step, we compute the cooling (sensible) loads, the latent loads and the total loads separately. This graph represents the loads for the hottest month in Accra.

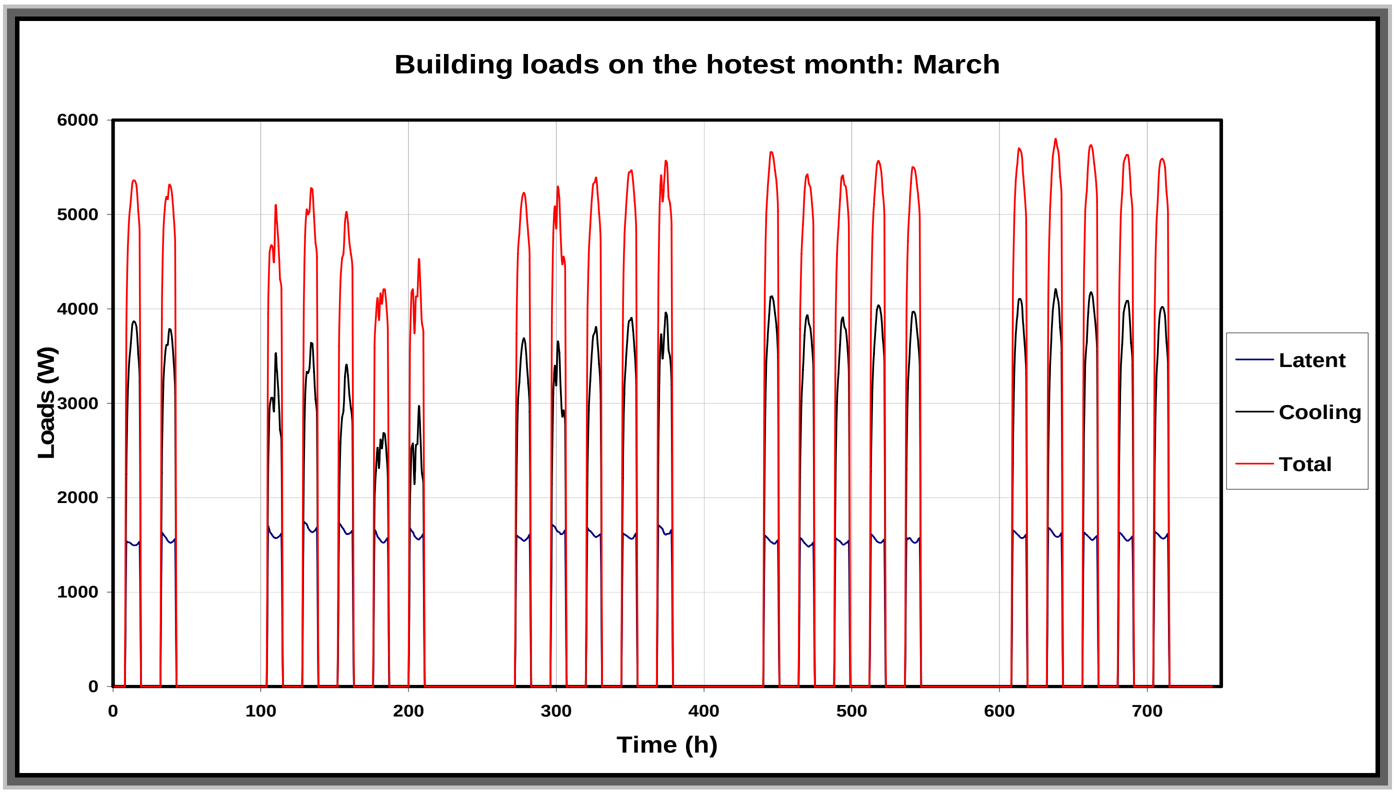


Fig.16: *Simulation on the hottest month: Latent, cooling (sensible) and total building loads*

The room is cooled from 8am to 6pm from Monday to Friday and the cooling system is switched off for the other hours according to the schedule of occupation. It can be noticed on **Figure16** that the month on March begins on Thursday. The cooling, latent and total loads are computed only during the device working time. Thus there are no loads to be computed every night and the whole week end because the cooling system is off as shown in the figure. It can be noted that the daily average latent load is quite stable for the whole month but the cooling loads deeply varies day after day in the month. Consequently, as shown in the graph, the total loads shape is mostly determined by the cooling loads. For the whole month, the maximum total daily loads are almost all above 5kW. This situation explains the extreme weather condition during the month. As shown in the graph, the maximum daily load is twenty times on twenty-two days (during the operating period) above 5kW but, our simulations proved that according to the room occupation schedule, the pick load day occurs in February 22nd with a corresponding maximum temperature of 35.4°C all over the year. The pick day is not necessary the hottest day of the year because according to the schedule the cooling system is off during the week end, which, for the test reference year weather data, has the maximum temperature of the year.

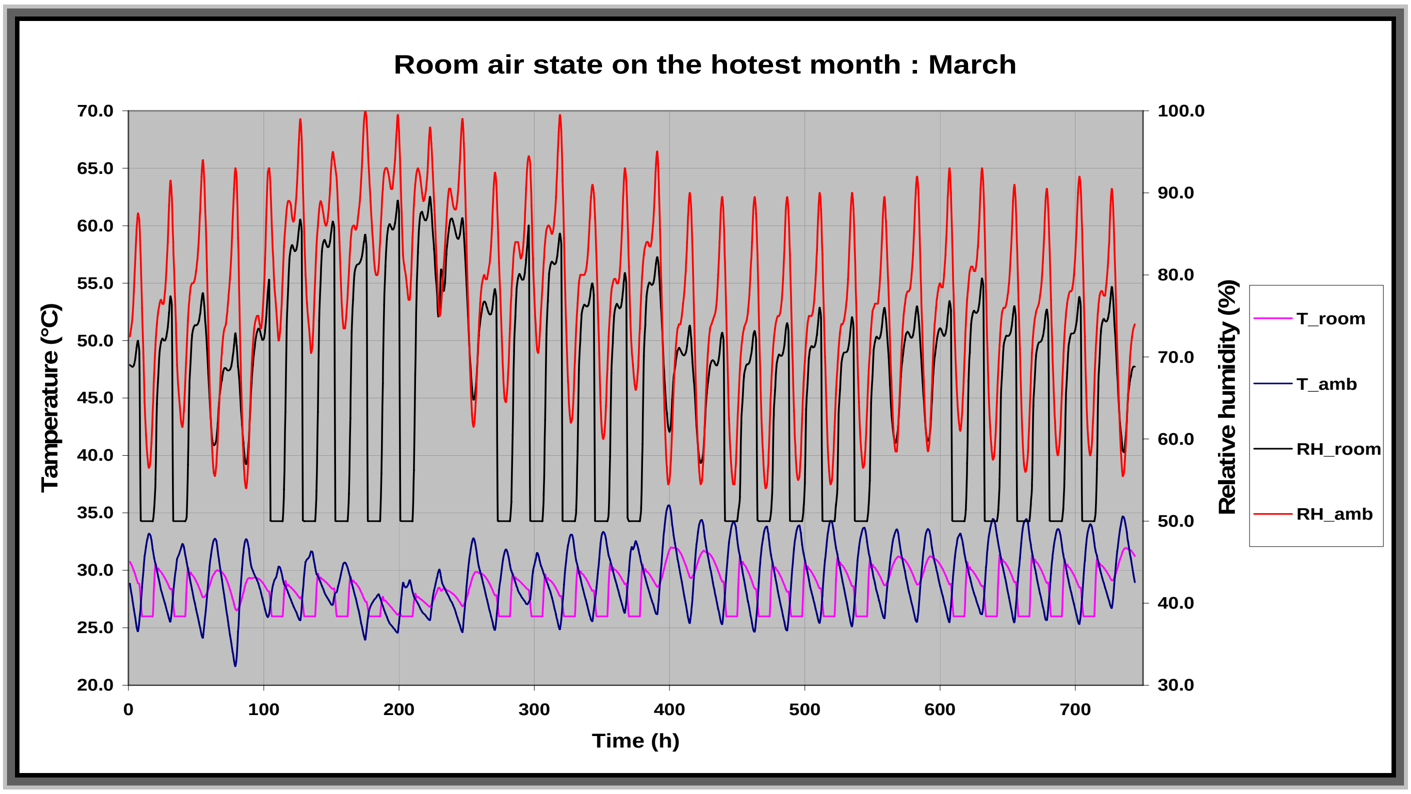


Fig.17: *Simulation on the hottest month: Room air and ambient RH and Temperature*

The relative humidity and the temperature of the room air have been followed during the yearly simulation in order to check if the predefined set point and schedule are respected. The above graph represents this room air parameter for the hottest month. It can be observed that the air parameters follow the predefined schedule as the above loads. The predefined set points for the room comfort are 26°C for the room air temperature and 50% for the relative humidity. We can see on the graph for the hottest month that the room air set points are respected throughout the month according to the schedule of occupation. During the workdays, the room air temperature and relative humidity follow the set points and for the week end, these parameters evolve freely according to the external temperature and infiltration rate due to the fact that the cooling system is off. For these hours of non occupation, only the thermal inertia and infiltration rate of the building determine the indoor temperature and humidity ratio. The load and room air parameters matches with the predefined occupation schedule. Because of the huge volume of data to be treated for the year (8760 value for each parameter), we just represented parameters for the pick period.

4.1.2- Daily simulation

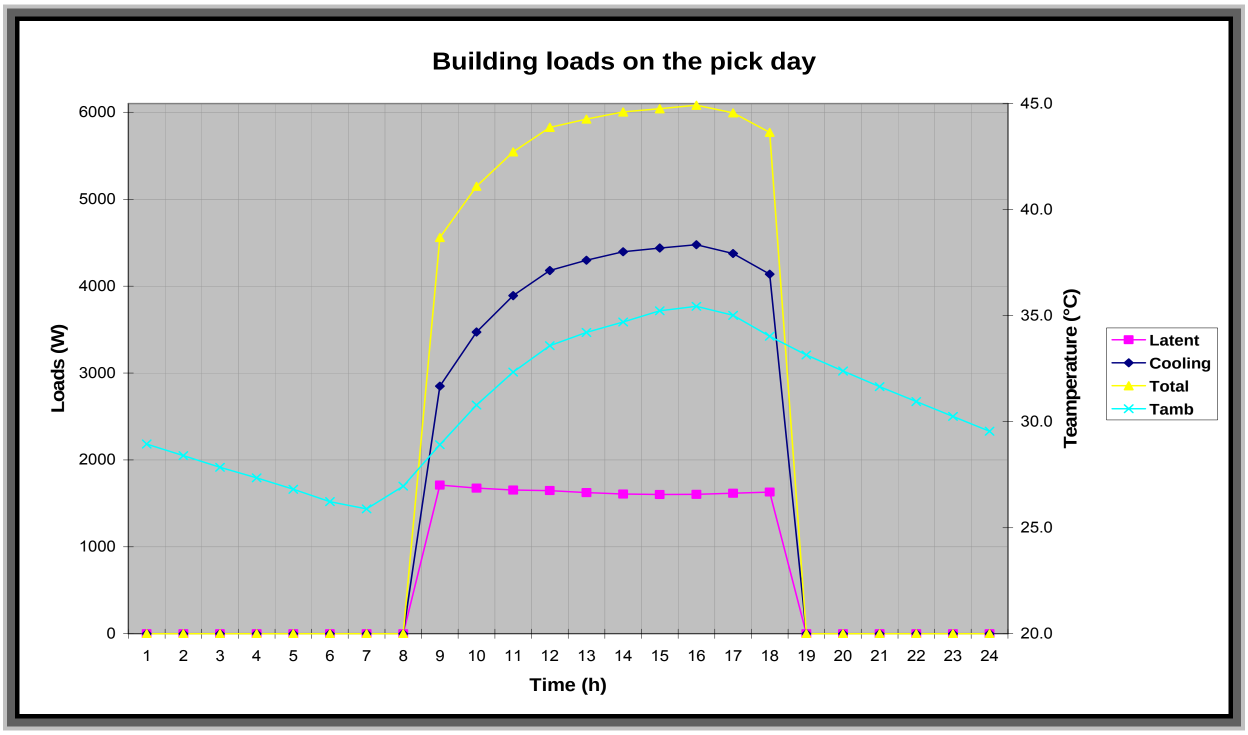


Fig.18: *Simulation on the pick day: Latent, cooling (sensible) and total building loads*

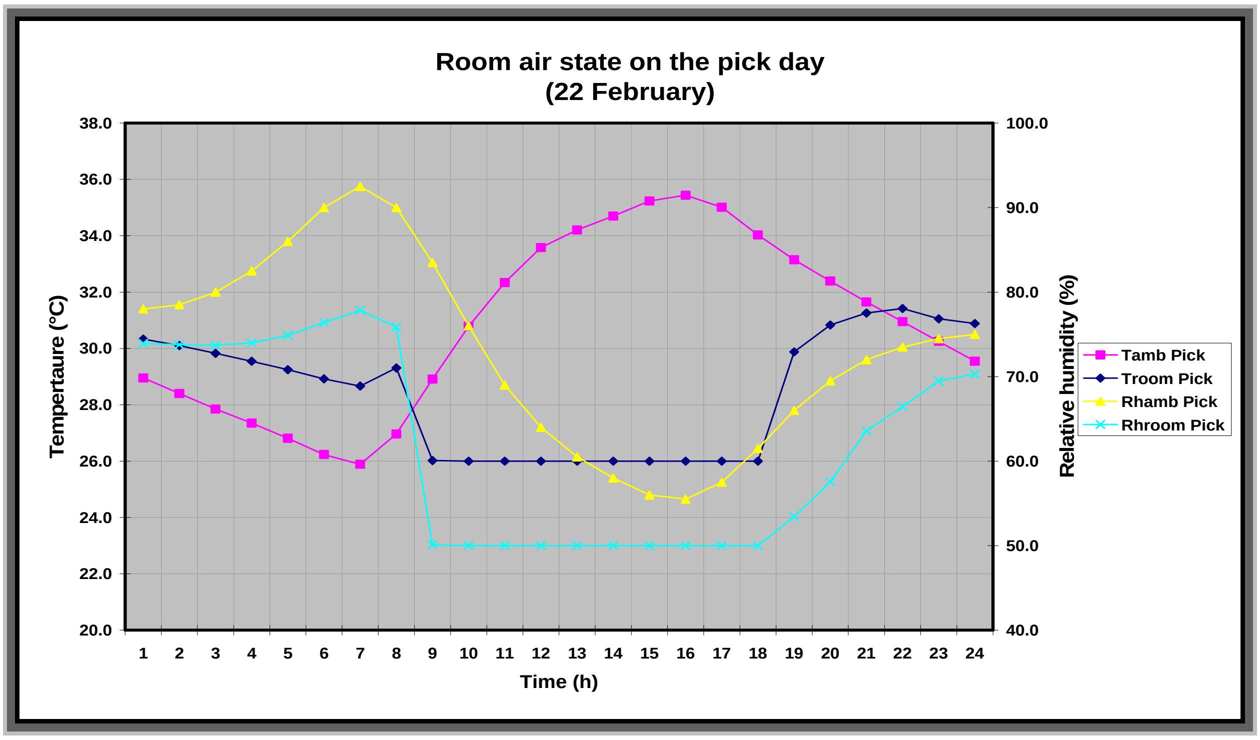


Fig.19: *Simulation on the pick day: Room air and ambient RH and Temperature*

In order to have a detailed view of the parameters simulated we represent here a zoom of the evolution of the loads and the room air parameter for the pick day. As described in the last chapter, the conference room is located at the second floor of a four floor building. The roof is a slab and its outside's extension (1.9m) plays a role of a horizontal shading device for the glazing in particular and the overall outside (north and south) wall in general. Thus for the whole day, there is no direct sunlight on the entire external wall and then on the glazing. Consequently, the heat flux by transmission is the main solar load component. In **Figure17** we notice that the latent load varies slightly during the day while the cooling load strongly varies with the period of the day. Consequently, as formerly noticed, the total loads are strongly dependent on the cooling load with a maximum value of 6 kW. Furthermore, it can be seen that the cooling load have approximately the same shape with the ambient temperature curve. This can be explained by the effect of the external horizontal shading device and is the proof that the heat flux by transmission is the main component of the solar loads.

4.1.3- Comparison with the simplified method calculation

In order to validate our results we compare the load on the pick day with the one gotten with the classical simplified method of building load calculation in tropical countries (see appendices for more details). The principle of the method is to define according to the climate a month of base with the air parameters (temperature and relative humidity) in order to approach the pick day. The loads are computed in order to simulate a desiccant cooling system. Then the air change is achieved in the building by mechanical ventilation. The ventilated air is supposed to be supplied at the set point temperature and relative humidity. Consequently, the ventilated air does not account for loads calculation. In addition, there is no direct sunlight on the building during the day which reduces the solar loads to transmission. The main latent loads are the infiltrated air and the one from occupants. For the pick day we have computed the load for different hours of the day and the results are compared to the one given by the simulation. **Table4** summarizes the entire computation.

Tab.4: *Comparison between the simulated load, the installed air conditioner power and the load calculated by the simplified method for the pick day.*

	Simulation TRNSYS	**Simplified method**
Date and air parameters: **22 Feb. at 12pm; T=33.6°C ; RH=64%; ω=21.4g/kg**		
Latent (W)	1624	1667
Sensible (W)	4298	4666
Total (W)	**5922**	**6333**
Date and air parameters : **22 Feb. at 14pm; T=34.7°C ; RH=58%; ω=20.6g/kg**		
Latent (W)	1608	1625
Sensible (W)	4396	5083
Total (W)	**6004**	**6708**
Date and air parameters: **22 Feb. at 16pm T=35.4°C ; RH=55.5% ; ω=20.5g/kg**		
Latent (W)	1604	1619
Sensible (W)	4477	5349
Total (W)	**6081**	**6968**

We can notice that the latent loads for both calculation methods are extremely close one to the other but, some slight differences are noted for the sensible loads. In fact, TRNSYS uses a more detailed method for the sensible heat transmission trough the walls by calculating the overall transmission coefficient according to the structure and layers thicknesses. Moreover, the simplified method sometimes can overestimates or underestimates the loads because ambient air parameters for load calculations have to be taken according to the month of base. This simplified method is used here just to show how close the results are; we can thereby conclude that the TRNSYS hourly loads can be used for desiccant cooling system simulation.

4.2- Desiccant system simulation, analysis and discussion

In order to investigate the use of the desiccant system for the cooling of the conference room, simulations of the overall system are done for all the year. The plant is an autonomous conventional cycle using solar driven heat. Thereby, as soon as the solar energy is converted into heat, it is directly used to heat the regeneration air flow. The room air parameters are followed and compared at each time step to the required indoor conditions. On another side, the inlet air temperature required for regeneration is hourly computed. Simulations are run for different collector surfaces and the outlet air temperature of the solar unit is compared to the regeneration inlet air in order to assess the optimum collector surface.

4.2.1- Optimum parameters of the system.

The pick cooling load determines the maximum air flow rate of the desiccant system. Due to the high degree of moisture in ambient air and the high density of occupation, we highly reduced the ambient air humidity ratio in the sorptive wheel in order to have the possibility to slightly humidify (drop in temperature, rise in humidity) the air before the room supply. This results in acceptable air parameters at the exit of the building and a high temperature for the inlet regeneration air flow for an optimum air flow rate. Simulations have been carried out for the year and particularly for the pick period in order to have the optimum inputs (air flow rate, set point for dehumidification, water flow rate for the humidification of the supply and exit building air).

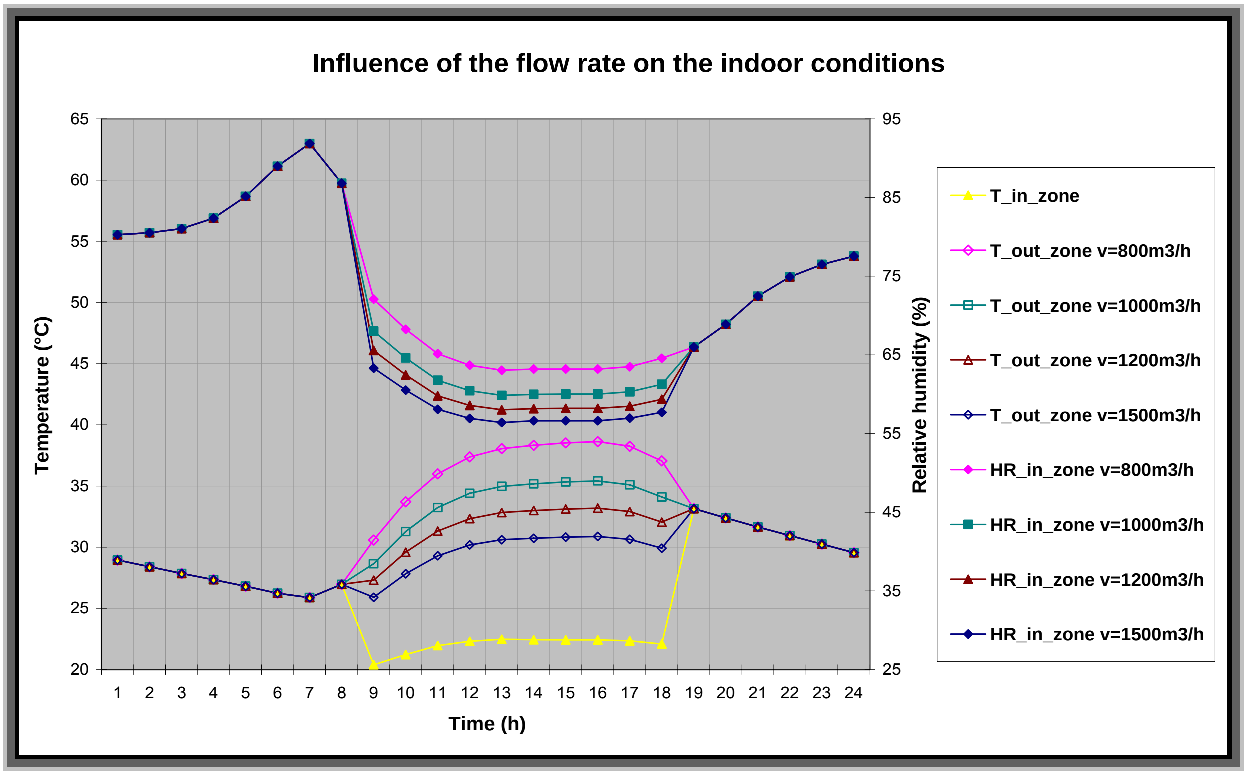


Fig.20: *Optimum parameter: Influence of the flow rate on the indoor conditions*

Figure20 represents the outlet building conditions as function of the air flow rate for fixed water flow rate and humidity ratio set point respectively in the humidifier and the sorptive wheel on the pick day. Indeed, desiccant systems are all air systems and the air flow rate is an important parameter to overcome the cooling loads. The building outlet conditions are deeply dependant on the air flow rate. A low flow rate leads to high temperature and humidity ratio outlet. We set the humidity ratio of the outlet process air to 0.008kg/kg in the sorptive wheel. This allows us to have the possibility to humidify the air before the supply to the building with the set point constraints (50%; 0.0106kg/kg; 26°C). For a minimum air change rate of 600m^3/h, this correspond to a maximum water moisture rate close to 2kg/h added to the air in the humidifier (taking the air density to 1.2kg/m^3). The minimum air change (600m^3/h) is not sufficient to overcome the sensible loads of the building (high outlet building temperature; high inlet building relative humidity). In this figure we can notice that an increase of the flow rate from 800 to 1500m^3/h brings the outlet temperature and the inlet relative humidity close to the requirements. On another side, an excess air flow rate can be source of discomfort according to the building volume or can lead to large device size. The plant studied by Henning in Riesa in 2001 was used in a 330 m^3 building with an air flow of 2700m^3/h. According to the building dimensions and the cooling loads, the optimum parameters are summarized in **Table5**.

Tab.5: *Optimum parameter of the system.*

Parameter	Sorptive wheel	Humidifier 1	Humidifier 2
Optimum air flow rate (m^3/h)	1500	1500	1500
Minimum air change (m^3/h)	600	600	600
Optimum water flow rate (kg/h)	-	2.6	10
Optimum HR set point (kg/kg)	0.008	-	-

4.2.2- Simulation with the optimum inputs

Figure21 shows the evolution of the air temperature in the cycle for the pick day. In this figure, the supply and the return air stream are represented by **blue** and **red** colour curves respectively. We can notice a very high regeneration temperature (around 82°C°). This situation is explained by the high humidity ratio of the locality. At the outlet of the sorptive wheel for a flow towards the indoor, the temperature is very high (up to 70°C). In fact, the adsorption process is exothermic and quite isenthalpic. Each water vapour particle's adsorption is followed by a release of an amount of heat equal to its heat of vaporisation plus an additional heat of sorption depending on the type of sorbent. This heat is used to warm the wheel and the surrounding air.

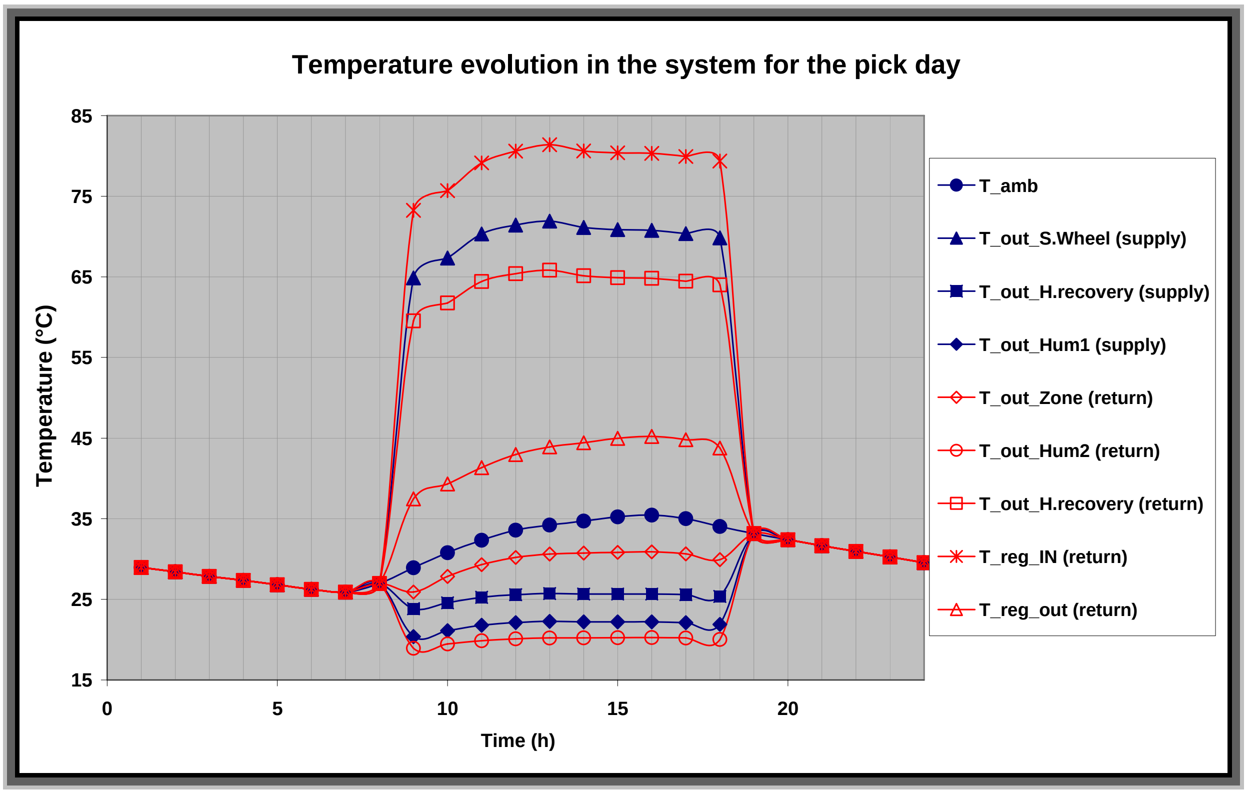


Fig.21: *Optimum inputs: Temperature evolution in the system on the pick day.*

It is also important to precise that the pick cooling day is not necessary the most humid day of the year. Consequently, the regeneration temperature for the pick day is not the maximum (89°C for the most humid day of the year) regeneration temperature of the year. The system operates with a high regeneration temperature because of the high humidity ratio in ambient air. This increase the solar unit size and then the investment cost.

Figure22 represents the humidity ratio of the air in the cycle for the pick day. In this figure, the supply and the return air stream are represented by **blue** and **red** colour curves respectively. We can note that the humidity ratio is maintained at the set point of 0.008kg/kg at the outlet of the sorptive wheel. Furthermore the humidity ratio of the supply air in the heat recovery is the same as the sorptive wheel outlet. This is explained by the fact that there is no condensation during the process (only sensible heat is indirectly exchanged between the supply and the exhaust flow). In addition, we can note that the adsorption process in the sorptive wheel brings at 3pm the humidity ratio of the ambient air from HRamb= 0.020kg/kg to HRout_S.Wheel (supply) =0.008 kg/kg which gives a variation of 0.012 kg/kg; then regeneration process brings the humidity ratio of the regeneration air from HRreg_IN=0.015 kg/kg to HRreg_out=0.027kg/kg which gives also a variation of 0.012kg/kg. Thereby, the adsorbed water vapour is completely regenerated by the return flow. In order to validate our results, this mass balance has been done for the other working hours and the results were coherent.

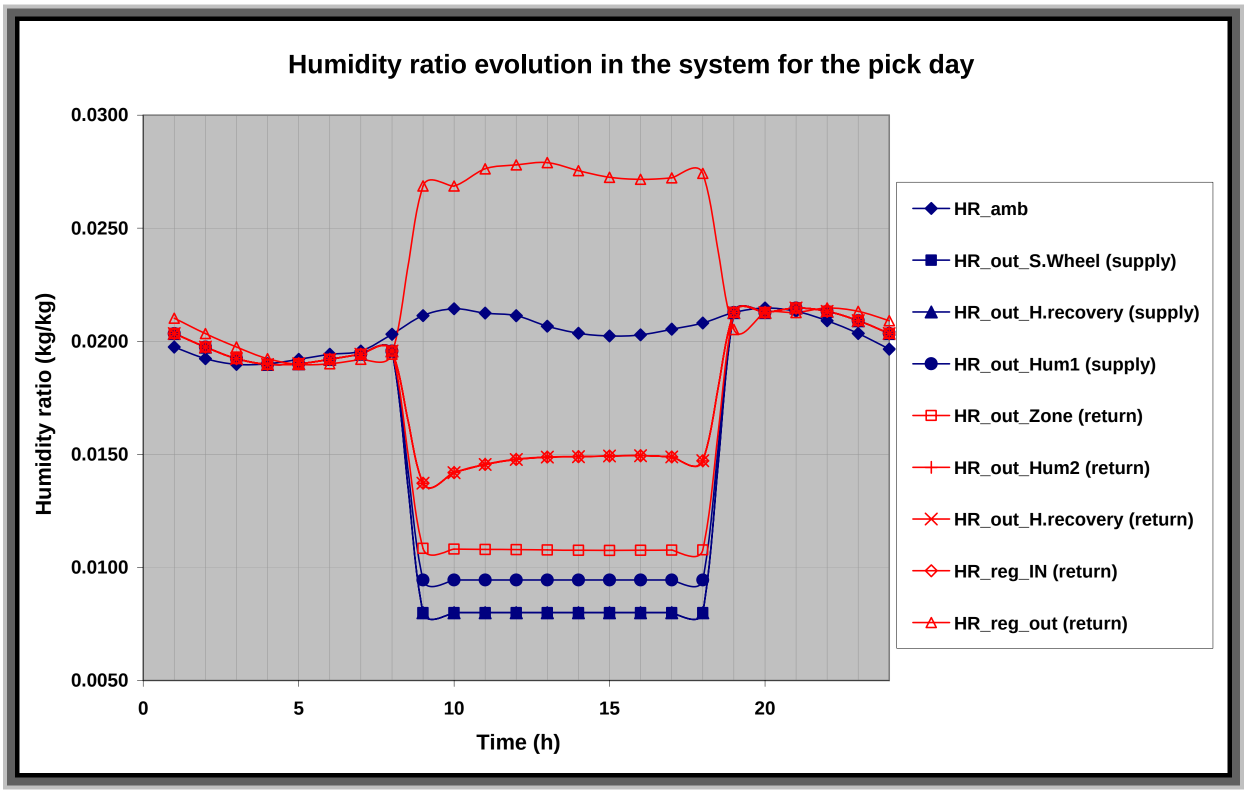


Fig.22: *Simulation on the pick day: Humidity ratio evolution in the system.*

As formerly said, the TRNSYS sorptive wheel component computes the regeneration air temperature from the inlet air parameters, the outlet humidity ratio set point and the inlet regeneration humidity ratio. The regeneration temperature hourly computed is the one that has to be provided by the solar unit in order to supply the simulated indoor conditions. In order to assess the optimum collector area, we have computed the outlet temperature from the solar unit for different surfaces. **Figure23** represents the temperature for the pick day. The regeneration air is preheated in the heat recovery during indirect sensible heat exchange before its entrance in the solar unit which role is to rise its temperature to the simulated requirement. We can note that the outlet collector temperature increases with the collector area. Due to the fact that the system is autonomous, the simulated regeneration temperature has to be reached for the whole day in order to provide the simulated indoor conditions. The solar unit outlet temperature is the image of the sunniness of the corresponding day. Considering the solar fraction as the number of hours during which the solar unit supplies the required regeneration temperature in a period of operation, our computations gives 0% for collector area less than 10m²; 50% for 14m² and 60% for 18m² on the pick day. The plant studied in Riesa by Henning was driven by a solar unit consisted of 20 m² of water collector and a back up thank of $2m^3$. Our computations show that an increase of the collector area up to 26m² does not change considerably the maximum solar fraction for the pick day and becomes on an economical point of view heavy. Consequently, the optimum area surface for the collector is taken to be 18m².

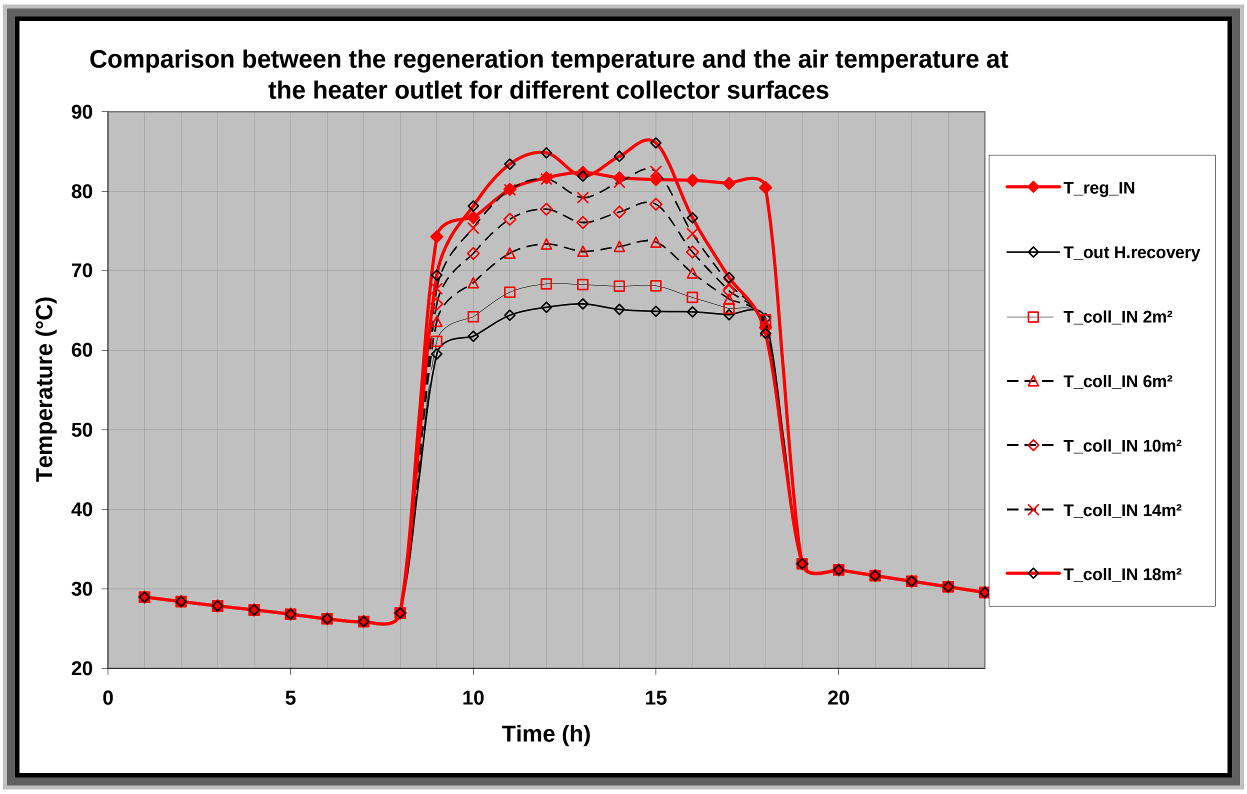


Fig.23: *Simulation on the pick day: Research of the optimum collector area.*

It can be noted that before 10am and after 3pm the solar unit is not able to supply the required temperature for the pick day thereby, a need of a back up source appears to be necessary. Furthermore, for the optimum collector area, our simulations have proved that during normal sunny days, an excess of energy is supplied between 10am and 3pm. A back up thank can be useful in order to delay the excess energy for the less sunny period of the evening. **Figure24** shows a sample normal sunny day simulated with the optimum parameters that confirms the optimization of the system by the use of a back up source.

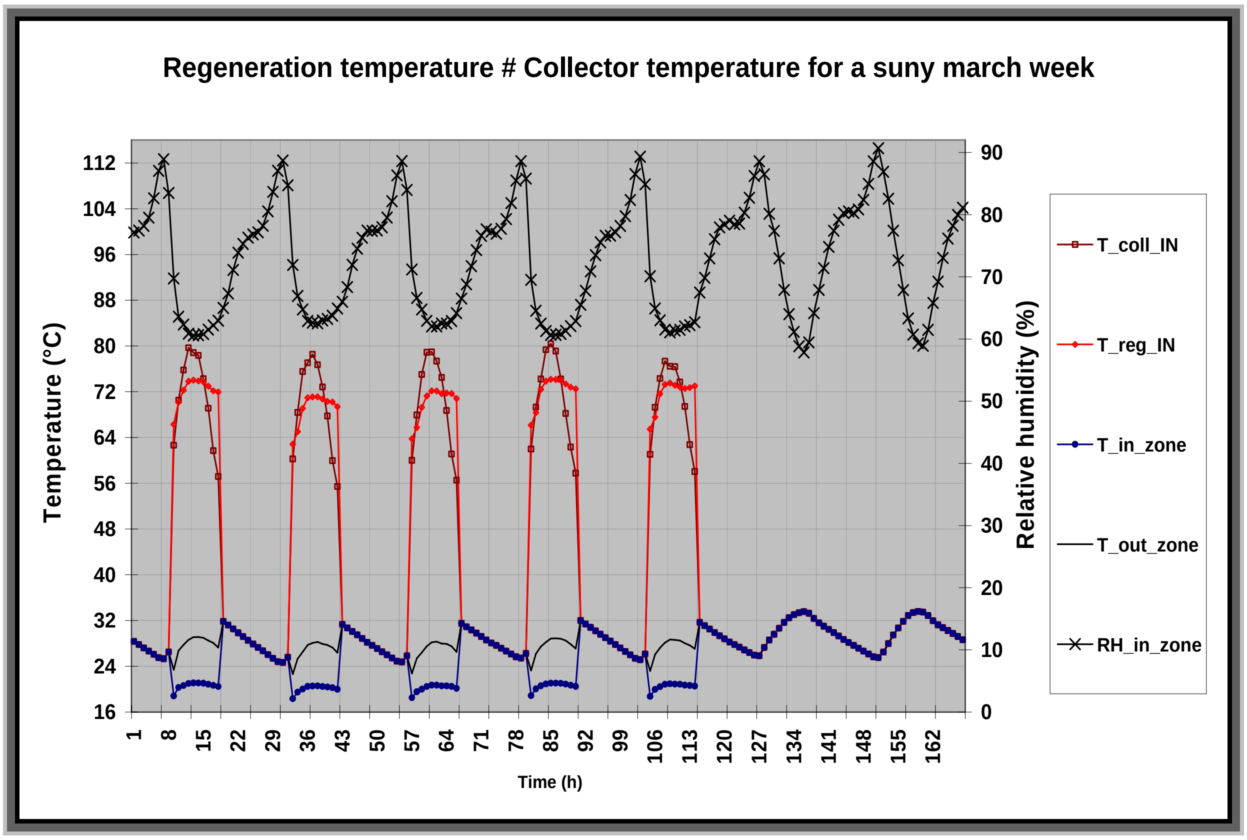


Fig.24: *Comparison between the regeneration temperature and the outlet temperature of the solar unit for a sunny week*

Also, for the overall year simulation, it can be noted that the plant is unable to supply rigorously the set point temperature and relative humidity in the room. During the hottest and sunny days, the outlet building temperature is close to 30°C while it drops close to 24°C for less hot days. For the overall year, the relative humidity fluctuates slightly around 60%. Our system is simulated with a constant flow rate but an optimisation can be made by a modulation of this flow rate for the less hot days for energy saving.

For more visualisation of the cycle, we have represented the evolution of the air in the psychometrics chart on the pick day at 1pm. When analysis of the adsorption (1-2) and regeneration (8-9) processes, we can easily conclude that the processes are quite isenthalpic as formerly mentioned. Furthermore, it is important to note that the air path in the chart changes with respect to the ambient conditions.

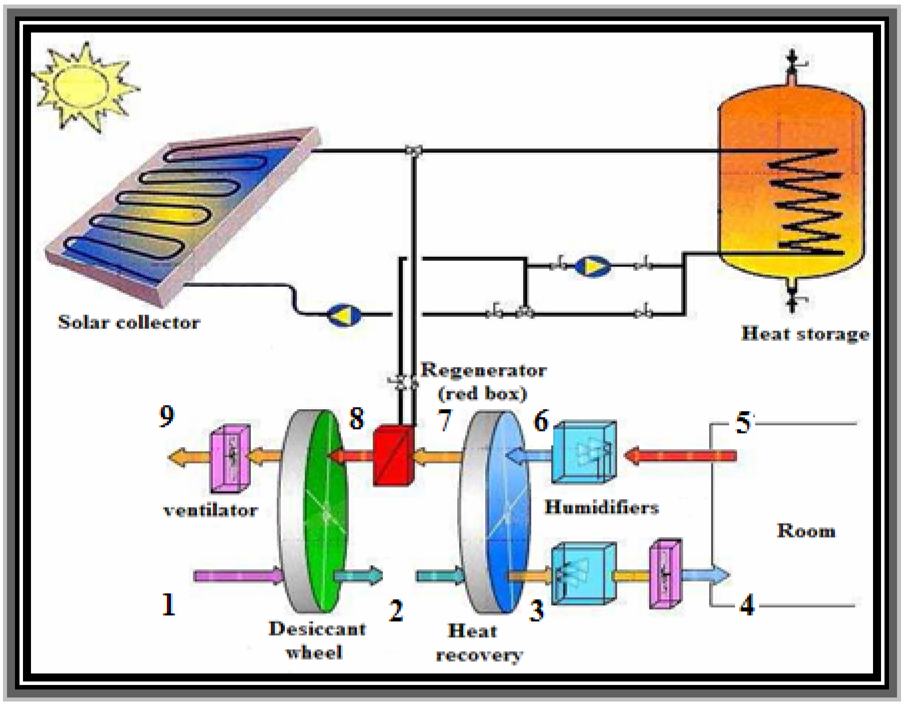


Fig. 25: *Evolution of the air in the cycle.*

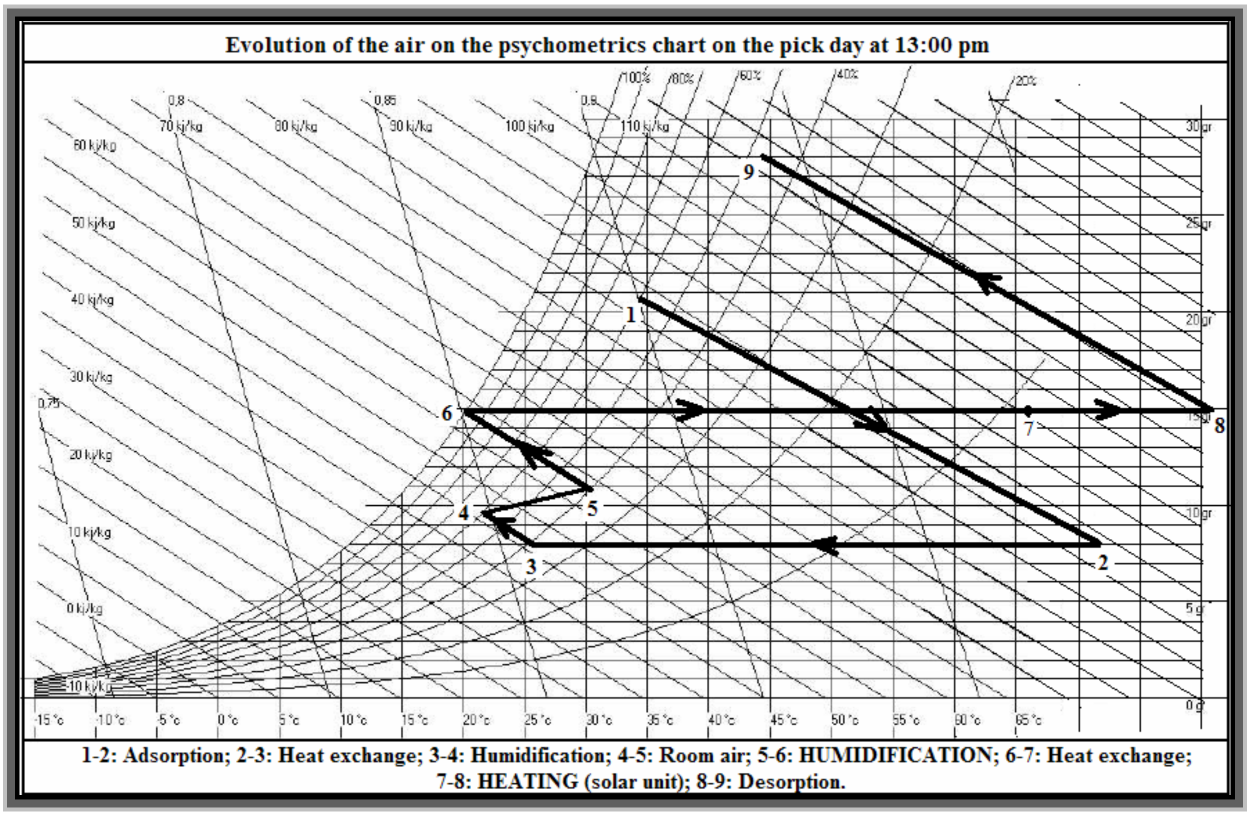


Fig.26: *Evolution of the air in the psychometric chart on the pick day*

The thermal COP is defined as the ratio of the cold provided (4-5) and the required driven heat (7-8) [20]. Furthermore, the electrical COP is defined as the ratio of the cold provided over the entire heat and electrical power. For the hours fully covered by the solar energy on the pick day, we have computed the thermal and electrical COP of the system. For the electrical COP, the power of some components has been chosen according to references found in literature [3] and for the others assumptions have been made. The power consumed by the plant during a time step of one hour is the sum of the power of all the components in operation during that time. The results for the pick day are shown in **Table6**.

Tab.6: *Value of the $COP_{thermal}$ and $COP_{electrical}$ for the sunny hours of the pick day*

Time (h)	Q_{cool} (kJ/h)	Qcoll (kJ/h)	P_{elect} (kJ/h)	$COP_{thermal}$	COP_{elect}
10	18600	25400	3124	0.73	0.65
11	20000	29400	3124	0.68	0.61
12	21000	30100	3124	0.70	0.63
13	21300	27900	3124	0.76	0.69
14	21600	29900	3124	0.72	0.65
15	21800	32800	3124	0.66	0.61

This table shows that the instantaneous thermal COP for an autonomous operation (supply temperature by the solar unit higher than the computed regeneration temperature) during the pick day fluctuates around a value of 0.7 as predicted in literature. On the other side, the electrical COP is obviously less than the thermal COP because of the auxiliary power consumption.

Conclusion

The main purpose of this chapter was to present the results of our simulation, to analyse and discuss them. Divided into two sections, the results of the building loads simulation have been first presented, analysed and compared with the simplified method of loads calculation in tropical countries. Afterwards, simulation of the solar desiccant plant has been presented and discussed for the overall year and specifically for the pick period. The results have shown the inability of an autonomous plant to meet the loads of all the hours of a sunny day but a storage thank has been found to be useful to delay the heat driven regeneration of the sunny hours for less sunny period of the day.

GENERAL CONCLUSION AND RECOMMENDATIONS

The main purpose of this work was to simulate and analyse the thermal loads of a conference room and to investigate the use of a solar desiccant evaporative cooling system with the transient software tool TRNSYS. In the first part of the results, we have presented the simulation of the load. Due to the building design, the cooling load has been found to be the major component in the total loads. A comparison with the simplified method has been used to show the closeness of both methods for the computation of the latent load; some slight differences due to approximations made in the simplified method for the computation of the sensible loads were noted. In the second part, the computed loads were used to investigate an autonomous solar desiccant autonomous cooling system. The analysis of the result has shown a high regeneration temperature due to the high humidity ratio of the site. Furthermore, it has been found that an autonomous solar desiccant cooling system will not be able to meet the required indoor conditions for the overall day. This is due to the non uniformity of the irradiation during the day. However, a storage tank has been found to be useful to delay the excess of energy to cover the later less sunny hours of the day. Also, for the less sunny hours of the morning, a back up energy has been found to be a complementary energy source in order to reach the regeneration temperature requirements. In addition, the sorptive wheel in our simulation highly dehumidifies the inlet air from a humidity ratio closed to 20g/kg to the set point humidity ratio of 8g/kg. Considering the high inlet flow rate this lead to a high regeneration temperature and consequently to a high collector surface compare to the building volume to be cooled. The following recommendations are then suggested for future works:

- Due to the inability of an autonomous solar desiccant cooling system to meet the indoor conditions for all the hours of a sunny day, we suggest an assessment of the need of back up energy for all the year, the computation of the optimum back up tank volume and the yearly simulations with a variable flow rate for the less hot day.
- Due to the high humidity ratio of the climatic zone, we suggest a study of the possibility of using a conventional dehumidifier to pre-dehumidify the ambient air at the inlet of the sorptive wheel. This study will lead to the optimization of the size of the cooling unit but should be followed by an economic feasibility study.
- Finally, we suggest an investigation of the use of an hybrid system combining the solar desiccant evaporative cooling and the conventional vapour compression system in the same climatic zone.

BIBLIOGRAPHY

Books and articles

Chadi Maalouf (2006), ''Étude du potentiel de rafraîchissement d'un système évaporatif à désorption avec régénération solaire'' ; *Ph-D thesis,* UFR Sciences Fondamentales et Sciences pour l'ingénieur, Spécialité Génie Civil, Université la Rochelle pp.1- 59.

Clausse M. (2003), ''Etude d'un procédé d'adsorption TSA (Temperature Swing Adsorption) à chauffage et refroidissement indirects'', *PhD Thesis*, pp. 21-22.

Dascalaki, Santanousris M. (1991), "Radiation trough partly covered building opening" Solar energy*, a journal of Renewable energy, vol.* 61, N° 6 pp. 355-367.

DITTMAR J. (1997), "Solar desiccant cooling : a pre –study of possibilities and limitations in Northern Europe", *Research training course E136*, Chalmers University of Technology, Göteborg, Sweden.

Djin P., Cherbuin O., Hildbrand C., Mayor J., (2003), ''La réfrigération solaire à adsorption'', *Ecole d'Ingénieurs de canton de Vaud*.

European Solar Thermal Industry Federation, ESTIF (2006), ''Key issue for Renewable heat in Europe'', *Solar Assisted Cooling – WP3, Task 3.5, Contract EIE/04/204/S07.38607*

Fatemeh Esfandiari Nia , Dolf van Paassen , Mohamad Hassan Saidi (2006), ''Modeling and simulation of desiccant wheel for air conditioning'' *Energy and Buildings* 38 (2006), 1230–1239

Henning, H. M. (2003), ''solar assisted air conditioning of building'', *International Energy Agency IAE.*

Henning H.M., Erpenbeck T., Hindenburg C., Santamaria I.S. (2001), "The potential of solar energy use in desiccant cooling cycles", *International Journal of Refrigeration*, pp. 220-229.

Höfker G., Eicker U., Lomas K., Eppel H. (2001), "Desiccant cooling with solar energy", *CIBSE publications*.

Hu Jing, Excell R.H.B. (1993), "Adsorptive properties of activated charcoal/methanol combination, Renewable Energy (1993), *An International Journal*, vol 3 N° 6/7 PP 567-575.

Institut de l'Energie et de l'Environnement de la Francophonie, IEPF (2002), ''Efficacité énergétique de la climatisation en région tropicale'', ISBN: 2-89481-012-1, Tome 1 p.vi.

International Standardisation Organisation ISO 7730

James P. Waltz, P.E, C.E.M (2000), "Computerized building energy simulation handbook"; pp164-169.

Joudi K.A., Dhaidan N.S. (2001), "Application of solar assisted heating and desiccant cooling systems for a domestic building". *Energy Conversion & Management*, 42, 2001, pp. 995-1022.

Jurinak, J.J., (1982), "Open Cycle Desiccant Cooling – Component Models and System Simulations," PhD Thesis, University of Wisconsin – Madison.

Mande S., Ghosh P.; Oertel K., Sprengel U. (2002), "Development of an Advanced Solar-hybrid Adsorption Cooling System for Decentralised Storage of Agricultural Products in India", *V.V.N. Kishore Tata Energy Research Institute New Delhi-India; Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V. Institut für Technische Thermodynamik Pfaffenwaldring Stuttgart, Germany.*

POHLMANN (1988), *Manuel technique du froid.*

Schultz, K.J. (1983), "The Performance of Desiccant Dehumidifier Air-Conditioning Systems Using Cooled Dehumidifiers," MS Thesis, University of Wisconsin – Madison, 1983.

Techajunta S, Chirarattananon S, Exell R.H.B. (1999), ''Experiments in a solar simulator on solid desiccant regeneration and air dehumidification for air conditioning in tropical humid climate''. *Renewable Energy* (1999); 17:549–68.

Uwe Franzke, Christian Seifert (2005), *Solar Assisted Air Conditioning of Buildings IEA Task 25, Subtask B: Design Tools and Simulation Programmes Documentation for the SolAC Programme Version 1.5.*

Internet sites

http://www.dtkit.it/files/notes/peltier_module/index.php

http://www.energie.arch.ucl.ac.be/cdrom/Climatisation/equipements/machinefrigorifique/cliquemachineabsorb.html.

http:// www.solarserver.de/index-e.html.

APPENDIX

The simplified method of the calculation of loads in tropical countries (IEPF).

The aim of the method is to quickly compute the thermal load of a building in a tropical country while using pre-defined coefficients in tables.

The principle of the method is to define a month of base (extremes conditions) with the corresponding ambient temperature and relative humidity.

Knowing the thermal characteristics of the building, the internal gains, the infiltration and the ventilation flow rate, the thermal load are computed as follow:

- **Transmission trough walls and glazing**

$$Q_{tr} = k.S.\Delta T \quad (W)$$

k = Overall transmission coefficient of the wall or glazing (W/m².K)
S = Area of the wall or glazing (m²)
ΔT = Temperature gradient between indoor and outdoor (°C)

- **Radiation on walls and glazing**

For walls the solar radiation load is given by the following relation:

$$Q_{Rw} = \alpha.F.S.R_m \quad (W)$$

For glazing the solar radiation load is given by the following relation:

$$Q_{Rg} = \alpha.g.S.R_g \quad (W)$$

α = absorption factor of the wall or glazing
F = Solar radiation factor ;
g = Reduction factor (due to the type of shading device)
S = Area of the wall or glazing (m²)

R_w = Intensity of radiation absorbed by the wall
R_g = Intensity of radiation absorbed by the glazing

- **Air change**

For the sensible gains, the thermal load is given by the following relation:

$$Q_{Sach} = 0{,}33.q_{ach}.(T_a - T_i) \quad (W)$$

For the latent gains, the thermal load is given by the following relation:

$$Q_{Lach} = 0{,}84.q_{ach}.(\omega_a - \omega_i) \quad (W)$$

q_{ach} =Air change flow rate (ventilation, infiltration, air change) (m3/h)
T_a = Air flow temperature (°C)
T_i = Indoor temperature (°C)
ω_a= Air change flow relative humidity (g/kg)
ω_i= Indoor air relative humidity (g/kg)

- **Internal gain**

The sensible gain from occupants is computed as follow:

$$Q_{So} = n.C_{So} \quad (W)$$

The latent gain from occupants is computed as follow:

$$Q_{Lo} = n.C_{Lo} \quad (W)$$

n = number of occupants,
C_{So} = Sensible heat produced by an occupant,
C_{Lo} = Latent heat produced by an occupant

The sensible gain from light is computed as follow:

$$Q_e = 1,25.P \ \ (W)$$

P= Power of a fluorescent tube (W)

The sensible gain from any other electric appliance is computed as follow:

$$Q_e = P \ \ (W)$$

P= Power of the appliance (W)

The coefficient k, α, F, g; the temperature gradient ΔT; the values of irradiation on wall and glazing R_w and R_g are taken in predefined tables with respect to the type of room, the total thickness and the colour of walls, the type of glazing and shading and finally the location of the site.