Modelling Analysis of Silica Gel / Water Adsorption Chiller Systems: A Review

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***Abstract*—This review paper takes into account the various modeling analysis that are done on an adsorption chiller bed/cooling systems. Adsorption systems compared to conventional VCRS and VARS are poor in performance and hence modeling and analysis of the aforesaid systems need to be done to overcome its limitations. This paper mainly focuses on three modes of analysis *viz.* thermodynamic model, lumped parameters model and heat and mass transfer model taking silica gel water as the working pair. The review work discusses the various modeling and analysis that has been done in this regard. Thermodynamic analysis involves simple methods whereas lumped parameter model takes into account the transient nature of the adsorption system. Heat and mass transfer model on the other hand involves complex partial differential equations, and numerical methods are required to solve them. However, by the use of thermodynamic model we can find the COP of the adsorption system, while by using heat and mass transfer model we can find every details of the adsorption cooling system as well as determine the temperature profile of the chiller bed. It can henceforth be concluded that while detailed results and analysis can be obtained with the help of heat and mass transfer model as compared to thermodynamic and lumped parameter model but the former one takes more time and is much more complicated than the other two.**

***Keywords*—modelling, adsorption chiller, silica gel-water, thermodynamic model, lumped parameter model, heat and mass transfer model.**

I. INTRODUCTION

The last two decade has witnessed a considerable increase in the research works pertaining to closed adsorption heat pumps and cooling systems. The reason for such a paradigm shift can be attributed to the fact that adsorption systems are a green alternative to the HVAC sector however they possess the main limitation of very low COP. Among the various review papers that were published in the last two decades, Meunier [1] concluded that a probable alternative to CFC's for refrigeration is a sorption system having a COP of approximately 1 coupled with cooling rates in the range of 300 to 1000W/Kg. He further summarized the various research works that are currently going on to enhance the efficiency of closed adsorption systems [2]. Similarly various research works are being carried forward to increase the quality of adsorption materials, improve performance of solid-vapour adsorption systems and developing various heat pump technologies [3,4]. Thus the progress of these thermally driven cold production systems has attracted researchers' attention and also proves to be a good alternative to conventional Vapour Compression Systems (VCRS) [5]. Adsorption cooling systems are waste heat driven and uses environmental friendly mode of cooling. Recently several research departments are achieving feats in various field using adsorption cooling systems.A long-life, reliable heat-powered sorption refrigeration system has been developed for spacecraft use at the Jet Propulsion Laboratory. Hence considering adsorption drivensystems as the future method of cooling, researchers are currently interested to understand the dynamic models and to perform various simulative studies of these systems to understand the theoretical steady state behavior and characteristics. Performing these parametric studies helps in mainly three ways: Firstly, it can produce extremely large volumes of results at virtually no added expense and it is very cheap, secondly it helps to ease the complex physical phenomenon which takes place in these systems and thirdly, it helps to perform analysis of those systems which are currently difficult to employ, for instance the rotary adsorption system [6]. Since these systems are huge with complex phenomenon, optimizations of these systems are required and proper model analysis helps in this regard.

This review work thus encompasses the various experimental works that have been carried out using various mathematical models. Among the various mathematical models the most commonly used models are: Thermodynamic Model, Lumped Parameter Model, Heat and Mass Transfer Model.

II. THERMODYNAMIC MODEL

This model only takes into account first and second law analysis and is mostly used to reveal the upper performance limit. However in this model, details of heat transfer are not considered and hence can be stated as one of the simplest analysis model. The expected performance of the system is determined from the first law while the quality of the process

and the reason for performance degradation can be determined from the second law [7]. This model is governed by the adsorption equilibrium equation which describes the adsorption phenomenon taking place within the system; either simple or complex.

Hassan [5] performed a thermodynamic differential analysis for adsorption refrigeration system based on DA adsorption equilibrium model. Experimental analysis was carried on an ice machine working with activated carbon-methanol as the working pair. The following conclusions were drawn:

- 92.56% of the input energy was used as activating energy of desorption.
- About 13.21% of the total energy drawn from the bed during the cooling phase was lost to the ambient in the form of sensible cooling.

A theoretical framework for the estimation of the isosteric heat of adsorption between an adsorbatevapour and an adsorbent solid was proposed by A.Chakrabort*yet al.* [8] based on the thermodynamic requirements of chemical equilibrium, Maxwell relations, and the entropy of the adsorbed phase. It is distinctive from the conventionally accepted Clausius-Claypron equation. Good agreement has been obtained for the various categories of adsorbent+adsorbate pair used where enthalpy of adsorption is either constant or increasing or decreasing with increase in the coverage of the adsorbate. A thermodynamic model on simple and regenerative cycles based on experimental data was proposed by Cacciola and Restuccia [9]. The model had been used to calculate the performances of the adsorption systems either in the heat pump or cooling operationand the useful heat/cold produced during a complete cycle per kilogram of adsorbent. The specific heat of refrigerant in the adsorbate phase was considered to be constant and equal to the specific heatof the gas at a given temperature and pressure. The model has been governed by the following adsorption equation:

$$\ln(p) = a(w) + \frac{b(w)}{T}$$

The enthalpy of heat adsorption is governed by:

$$b(w) = b_o + b_1 w + b_2 w^2 + b_3 w^3 = \frac{\Delta H(w)}{R}$$

Three adsorbent/adsorbate pairs have been compared in this model *viz.* 4A zeolite-water, 13X zeolite-water, AC35 activated carbon–methanol. Simulative results dictated the advantage of zeolite/water for domestic purpose as compared to other adsorbent/adsorbate pair. of lately several simulations have been carried out on the adsorption chiller taking into consideration various assumptions. Shelton et al. [10] developed a thermodynamic model for the thermal wave adsorption cycle, with certain assumptions as stated below:

- The temperature and adsorption profiles in the bed behave as square waves.
- The waves were assumed to stop short of the bed ends to account for realistic and finite wavelengths.

This model was successful in providing a good first order result. To achieve a more realistic view of the adsorption system a ramp wave was taken into considerate analysis along with a few assumptions [11]:

- The temperature was linear and the adsorption profile was obtained as a segmentedramp based on the temperature at the midpoint of the ramp.
- The ramp wave had a steady-state wavy length which was related to the adsorptionbed thermal design.

Critoph [12] studied the performance limitations of adsorption cycles for solar cooling, and established a simple model based on a general study of the cycle thermodynamics. The following assumptions were made in his analysis:

- The isosteres on the Clapyeron diagram were indeed linear.
- Constant heat source and sink temperature.
- The liquid specific heat was assumed to be numerically equal to about 0.2% of that of the latent heat.
- The temperature at the end of adsorption was equal to the condensing temperature.
- The specific heat of the adsorbed phase was first considered to be of liquid phase,and then the sensible heat to the adsorbed phase in desorption was assumed tobe equal to that needed to raise the mean mass of adsorbent during desorption tothe final temperature at the end of generation.

In this case the Dubinin-Astakhov (D-A) equation has been used as the Adsorption Equilibrium Equation as

$$q = W_o \rho(T) e^{-(\frac{A}{\beta E_o})^n}$$

The Enthalpy of Adsorption has been given by

$$\Delta H = \frac{R ln(\frac{P_2}{P_1})}{\frac{1}{T_1} - \frac{1}{T_2}}$$

The model was used to predict cycle COPs based on limited data available for chosen refrigerants and carbons. With activated charcoal as adsorbent, especially, it was found that,

methanol, acetonitrile, methyl amine, and NO_2 are suitable among different refrigerants that are sub-atmospheric at -10 °C, but methanol gave the best COP. A similar study of refrigerants that will always be above atmospheric pressure suggests that ammonia, formaldehyde, and SO_2 are the best choice (in given order).

Douss and Meunier [13] proposed an equilibrium model which was based on heat and mass balances for a cascading adsorption cycle. In this method an active carbon/methanol cycle was topped by a zeolite water cycle. Performing simulative studies the following results were achieved [14][15]:

- The cooling COP was predicted to be around 0.95.
- The heating COP was predicted to be around 1.54.
- The deviation from the experimental results was within a range of ±10%.

However, the system was not so good on output heat from the zeolite adsorber and the input heat on to the active carbon adsorber, though it showed good results on condensation and evaporation. The reason for such a behavior can be accounted for mainly two reasons:

- Due to cascading cycles the driving heat supplied by the boiler decreases.
- Dubinin'slawused to represent active carbon methanol underestimate methanol cycling which wasprobably due to the fact that evaporating and adsorbing temperatures are close toeachother.

Gui and Wang [16] established a practical model for an reversible three-heat-reservoir cycle for a heat regeneration adsorption air-conditioning system. Fig. 1 shows the schematic diagram for the following.

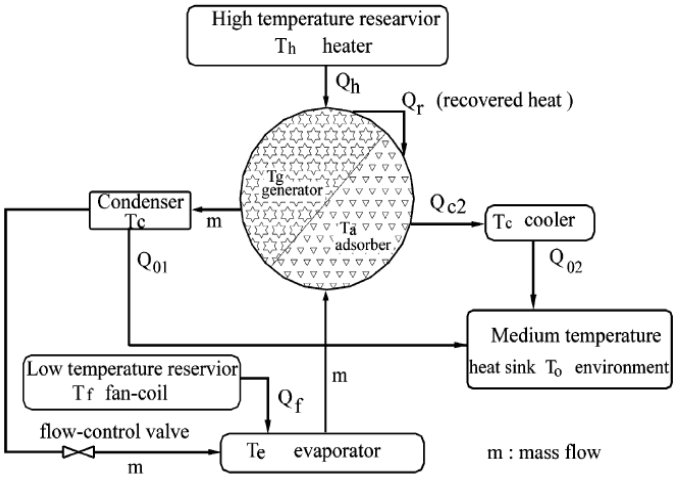

Figure 1: Schematic of an Adsorption Cooling System using three heat reservoir model.

The Enthalpy of Adsorption $\Delta^{\Delta}H$ has been assumed to be constant. The system works in the following manner:

- High temperature reservoir (represented by heater temperature, (T_h) supplies drive power (Q_h) for generator.
- Low temperature reservoir (represented by temperature of supply-air from fancoil, T_f) obtains latent heat cooling power (Q_f) from evaporator
- Heat sink (represented by ambient temperature, T_0) at takes away the heat ($Q_{01}$and Q_{02}) produced in condenser and adsorber respectively.

The major governing equation in the above model is based on the first and second laws of thermodynamics and has is a Modified Dubinin-Astakhov (D-A) equation as:

$$q = q_o e^{-k(\frac{T}{T_{sat}}-1)^n}$$

The following assumptions were made in this system:

- The heat leak and internalirreversibility in the cycle was neglected.
- The adsorption process was at equilibrium.

By constructing a prototype for the same it was found that the real thermodynamic cycle was similar to that of the ideal cycle [6].Gui*et al.* [17] further investigated the three reservoir model and four main performance indices were studied *viz.*Coefficient of amplification (COA), Specific heating power (SHP), Heat-recovery ratio and Second law efficiency. Their results indicated that the experimental result was close to simulation with the agreement of COA being within 8% and the agreement of SHP within 4%.

In other scenarios, Llobet and Goetz [18] have modeled a rotary system for the continuous operation using the concept of heat regeneration in a steady state.The model is in the form of counter flow heat exchanger in series. Moreoverthe absence of valves makes the installation extremely reliable.In the isosteric cooling zone, the adsorbent block consists of activated carbon, expanded graphite, composition of refrigerant and the metallic mass of the adsorber. Moreover in the adsorption zone, the adsorbent additionally takes into account two more factors: the change in composition of the refrigerant and the production of heat due to adsorption.Several assumptions were made in developing the model:

- The conduction heat transfer between the adsorbent and the adsorbers and desorbers,were assumed to be negligible compared to the heat transfer.
- During adsorption and desorption phases, the operating pressures was corresponding to that of evaporators and condensers.
- All elements were assumed to have equivalent flow rate.

The model used the generalized Dubinin-Astakhov (D-A)

equation as used in [12]. However, it employed a different equation for calculating the enthalpy of adsorption as :

$$Q_{st}(T, P_{eva}) = RT^2 \left[\frac{\partial \ln(p)}{\partial t}\right] = \Delta NH_3 + A + \frac{2.510^{-3} T\beta^n {E_o}^n A^{1-n}}{n}$$

The results also showed the presence of an optimal regeneration temperature which is about 170 °C for active carbon pair. Several different activated carbons were tested, and it was found that PX21 gives the highest COP due to its greater micropore volume.

Thus it can be concluded that thermodynamic model performs the most basic type of analysis of the chiller bed. From the experiments that were conducted it can be inferred for domestic purpose zeolite water should be used as the adsorbent+adsorbate pair while considering that the liquid specific heat to be numerically equal to about 0.2% of that of the latent heat methanol gives the best COP as sub atmospheric condition and ammonia gives the best COP for normal atmospheric condition. However the latter involves the problem of toxicity and is not suitable for domestic approach. Moreover while performing simulations if the temperature and adsorption profile is considered ramp wave type then a more realistic view can be achieved.

II. LUMPED PARAMETER MODEL

To take into the account the dynamic nature of the various models it was henceforth necessary to make analysis using Lumped Parameters Model as in this model the temperature and the mass content of the adsorbed phase changes with time. However it involves the following basic assumptions [19][6]:

- The mass-transfer rate inside the adsorbent layer controlsthe kinetics of sorption.
- Both temperature and pressure are assumed to be uniform in theadsorber. However, this assumption would be valid if the effective thermal conductivity of the adsorber is large enough to maintain a uniform temperature throughout the entire adsorbent layer.
- Both solid and gas phases exist at a thermodynamic equilibrium.

Cho and Kim [19], encompassed the lumped parameters model on the basis of three basic equations *viz.* energy balance equation, mass balance equation and adsorption equilibrium equation. For a desorption process the energy balance equation can be stated as:

$$\left(m_{mt}C_{pmt} + m_z C_{pz} + m_z q C_{pa}\right)\frac{dT_z}{dt} = m_z \Delta H \frac{dq}{dt} + \emptyset_{w\to z}$$

Similarly for the adsorption process, the energy balance equation can be stated as:

$$\left(m_{mt}C_{pmt} + m_z C_{pz} + m_z q C_{pa}\right)\frac{dT_z}{dt} = -m_z \Delta H \frac{dq}{dt} + \emptyset_{w\to z} + m_z C_{pa}(T_e - T_z)\frac{dq}{dt}$$

Here the symbol $\emptyset_{w\to z}$refers to the heat transferred from the heating or cooling medium. Similarly the mass balance equation for the adsorption system was given as:

$$m_z \frac{dq}{dt} + \frac{dm_{ae}}{dt} = 0$$

Where m_{ae} is the mass of the adsorbate in the evaporator. The adsorption equilibrium equation was summarized by the Simplified Freundlich's equation as:

$$q = q_{sat}\left(\frac{P}{P_{sat}}\right)^{1/n}$$

$$q_{sat} = 0.522\ {}^{kg}/_{kg}, n = 1.6$$

A simple lumped parameter model was constructed by Douss and Meunier [15] for two adsorbers. The model considered that each component of the system was homogenous. This model was however limited duly to water falling film evaporators and water condenser heat exchangers. During experimental study some numerical instabilities were realized, for relatively small time steps. Cho *et al.* [19] also presented similar lumped parameter model in which the sensible heat in the continuous recirculating refrigerant was included in the homogeneous model along with the heat transported during adsorption and desorption process. The overall heat-transfer coefficientfor the three components (adsorber, condenser, and evaporator) which have been estimated from the temperature and the flow rate have been used in the simulation. A generalized D-A equation has been used for this purpose. The performance of the model as determined experimentally was in agreement with the simulative results. The effect of heat transfer rate by the individual components on the cold generation capacity was determined by performing parametric studies. He further suggested that by modifying the heat-transfer rates of the condenser and adsorber, the thermal performance could be improved by about three times. A numerical simulation of a two-reactor adsorption heat pump was performed by Cacciola*et al.*[20] by taking into account the heat recovery system. The following assumptions were made in the model:

- Considering the adsorption kinetics to be in equilibrium.
- There is no temperature change in the reactors.

The governing energy balance equations were derived by

considering the efficiencies of various components of the system. These equations were then solved numerically by converting them to non-dimensional form and synchronizing them by varying the time step. Zeolite-Water pair was used for this regard and the results obtained experimentally [21] were in agreement with the one in [15]. Optimization of the system components were henceforth performed to obtain maximum performance [22]. Further Cacciola*et al.* [23] presented a simplified dynamic model in integral form, to evaluate the performance of an adsorption heat pump when heat transfer in the adsorbent reactors is the only cycle-time limiting factor. Time equation and energy equation were the governing equations for this model. The time equation was used to calculate the time period of different phases.The simulation aimed to study the effect of an increased amount of metal in the adsorbent bed on the COP and specific power of the system.It was shown that an increase in the heat capacity ratio of the metal and the dry zeolite, increases the heat transfer inside the reactor beds. Although an improvement in heat transfer can be achieved by increasing the metal content of the adsorber bed, but it causes a reduction in the COP of the system and this can eventually increase the investment cost per Watt obtained. Hence, these factor needs to be considered when the effort is being made to increase the heat transfer in the reactor beds.

Sami and Tribes[24] presented an improved lumped parameter model for single and double adsorber with heat recovery. Conservation equations and Isosteric equation of state have been used for model simulation. The heating phase equation is similar to the equations used by Douss and Meunier [15][6]. However for the cooling phase, the equation contains an additional term to account for the thermal effects due to the flow of refrigerant vapor from the evaporator to the adsorber. The model was discretized by adding sub models to evaluate the performance of the system. By applying discretized governing differential equations for each control volume it was concluded that there was a significant improvement in the thermal behavior as compared to the works stated in [15]. Experimental data of a double adsorber cycle with heat recovery had been simulated to assess the validity of their proposed model inpredicting the adsorption cascading cycle. It was found that the model predicted the temperature of the adsorber system very efficiently and is in synchronization with the experimental data. Further simulations were carried on using the pair active carbon and HCFC-123/HCFC-124 mixture (since it has a high boiling temperature). Simulation results indicated that lower heat capacities were obtained with the use of the HCFCs mixture.

Wu *et al.* [25] developed a model similar to the one in [24]. Here the operational parameters were determined using Dittus–Boelter correlation for smooth tubes and hence the experimental values were in a better agreement with the simulation results.

Critoph [26][27] proposed a lumped model to analyze the convective thermal wave which is part of a patented cycle, using heat transfer intensification to achieve both high efficiency and small size from a solid adsorption cycle. He utilized a packed bed of inert material [28] to store heat between the adsorption and desorption phases of the cycle. Greater is the degree of regeneration, greater is the COP. The simulation predicted a cycle COP of 0.95 when evaporating at 0^{o}C and condensing at 42^{o}C. However, this model was not validated by comparing with any experimental data.

Sakoda et al. [29][30] proposed a model which takes into account both adsorption properties and apparatus characteristics on the solar powered adsorption cooling systemusing silica-gel and water pair. The model includes three main equations such as mass balance equation of adsorbate, heat balance equation of the packed beds of adsorbents and a separate heat balance equation for the evaporator. In the model, the adsorption uptake was approximately given by the linear driving force (LDF) expressed by the difference of the amountadsorbed (q), and the maximum amount adsorbed (q_o) in equilibrium at certain pressure conditions.

$$\frac{dq}{dt} = 15\frac{D_{so}\left(-\frac{E_a}{RT}\right)}{{R_p}^2}(q_o - q)$$

To improve the simulative and experimental results the work was further extended [30] by considering different temperatures and the between the container of adsorbents and the adsorbent particles. The following results were henceforth concluded:

- The solar COP of a system is controlled by the efficiency givenas the ratio of the heat used for regeneration of adsorbents to the total solar heatinput.
- The efficiency is governed by the heat transfer area between thecontainer of adsorbents and the inner adsorbent particles.

Saha*et al.* [31] performed a similar model as in [29] comprising of a two bed silica gel-water adsorption chiller.Freundlich equation was employed to obtain the adsorption equilibrium equation.The simulation results showed that operating temperature and flow rate of the water were the most defining parameters for the COP of the system. The governing equation for the same can be written as:

$$q = q_{sat}\left(\frac{P}{P_{sat}}\right)^{1/n}; q_{sat} = 0.346\ {}^{Kg}/_{Kg}; n = 1.6$$

Performing experimental studies [32] it was concluded that the chiller was operational with a hot water-inlet temperature of 50°C, and the highest experimentalvalues of the COP, greater than 0.4 were obtained when this water-inlet temperature is made in combination with cooling water at 20°C. Saha*et al.* [33] further investigated analytically the performance of a thermally driven, advanced three-stage

adsorption chiller utilizing low-grade waste heat of 50°C and lower temperaturesas the driving heat source, in combination with a heat sink (cooling water) of 30°C. Simulative results concluded that the three-stage chiller can be operated with heat sources of 50°C and 40°C in combination with cooling source of 39°C and 30°C, respectively.

Chua *et al.* [34] further investigated Saha's model [33] and improved the simulation program by reconstructing the governing equation using the number of discrete elements in the heat exchanging tubes of the beds, evaporator and condenser in order to account for the accurate temperature variation at different sections of the tubes. Results showed that the chiller was able to achieve a unique cyclic-steady-state condition within 1800sec. It consist of two chiller beds: while one is used to cool by maintaining the adsorption process, the other is heated for desorption. The role reversal was achieved by switching the flow of heat source and coolant in the beds.Results further confirmed that by judiciously selecting the switching time, the same favorable conditions can equally be achieved and this can be a cost effective option.

Critoph [35] patented a new, continuous rotary adsorption refrigeration system which was similar to the model in [18]. Fig.2 shows the schematic of a section of the rotary system.

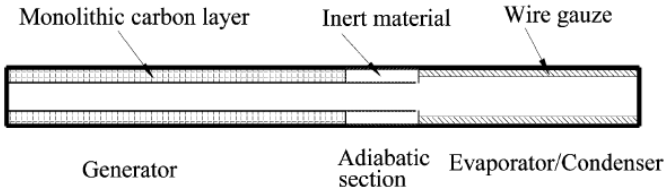

Figure 2: Schematic of a section of the rotary system

The refrigerant flowing in the module is similar tothat of the working media in a heat pipe. A prototype unit was fabricated and tested at laboratory scale. Using simple governing equations, the performance of the above system, consisting of 32 modules, was predicted. The governing equation for the same can be obtained as:

$$q = q_o e^{-k(\frac{T}{T_{sat}}-1)^n}$$

Here Monolithic carbon—Ammonia was used as the Adsorbent–adsorbate pair. The effect of key parameters such as thermal capacity ratio, number of modules, and generator heat transfer coefficient and evaporator air inlet temperature on the system performance was also studied.

Here it can henceforth be concluded that Lumped Parameter modelling takes into account the dynamic nature of the various models and produces much detailed analysis of the system in comparison to Thermodynamic modelling. From the various research works that were carried forward it can be inferred that including sensible heat of the circulating refrigerant into account while analysing the homogenous model provides a much more realistic results. Moreover heat transfer rates of the condenser and the evaporator needs to improved to increase the overall thermal performance of the system. However increase in heat transfer rates causes a reduction in the COP of the system and henceforth the system needs to be optimized on both fronts. Moreover use of inertia materials such as metals to store heat is a good and feasible solution and hence more efforts are needed in this regard.However to achieve a greater understanding of the complex adsorption phenomenon in different dimensions, a model much more advanced than the lumped parameter model was henceforth necessary. This led to the development of heat and mass transfer models.

III. HEAT AND MASS TRANSFER MODEL

With the increase in demand for a much more insight into the complex adsorption phenomenon, it was imperative to develop models based on heat and mass transfer analysis. The simulations based on heat and mass transfer are very significant, since they give insight into the dynamics of the adsorber in an adsorbent cooling system.A heat and mass transfer model is featured in which temperature or mass content of adsorbate varies not only with time but also with space and the governing equations are always partial differential equations. Based on the geometry of the adsorber, the models can be grouped under one-dimensional, two-dimensional and three-dimensional models.

The heat and mass transfer models are based on four primary equations *viz.*energy balance equation, mass conservation equation, momentum equation and state equation of the adsorbent-adsorbate system. Considering the system to be one dimensional, the governing equations can be stated as below:

The mass conservation equation for the system as obtained was:

$$\varepsilon \frac{\partial \rho_v}{\partial t} + \frac{\partial (\rho_v u)}{\partial x} + \rho_z \frac{\partial q}{\partial t} = 0$$

The momentum balance equation for the same can be stated as:

$$\frac{\partial \rho u_v}{\partial t} + \frac{\partial \rho u_v u_v}{\partial t} = -\frac{\partial \rho}{\partial x} - \frac{\partial}{\partial x}(\mu \frac{\partial u_v}{\partial x})$$

The energy balance equation for the system can be obtained for two phase: Vapor and Solid adsorbent.

Vapor phase equation:

$$\epsilon \frac{\partial \rho_v C_{pv} T_v}{\partial t} + \frac{\partial \rho_v C_{pv} u_v T_v}{\partial t} = \frac{\partial}{\partial t}\left(\epsilon K_v \frac{\partial T_v}{\partial x}\right) + \frac{\partial (C_{pv} \rho_z q)}{\partial t}(T_v - T_z) - h v_z (T_v - T_z)$$

Solid Adsorbent phase equation:

$$\rho_z\left(C_{pz} + C_{pa}q\right)\frac{\partial T_v}{\partial t} = \frac{\partial}{\partial x}\left[K_z(1-\epsilon)\frac{\partial T_z}{\partial x}\right] + \rho_z \Delta H \frac{\partial q}{\partial t} + hv_z(T_v - T_z)$$

The complexity and nonlinearity of such coupled heat and mass transfer models in general exclude the possibility of having an analytical solution. Therefore, numerical methods are the only feasible alternative to meet the requirements for simulation ofadsorbent bed dynamics. The numerical methods that are used in this regard are :

- Finite Difference Method
- Finite Volume Method
- Finite Element Method

Mostly Finite Difference Method is applied to heat and mass transfer analysis due to its simplicity and efficiency. However while applying these methods some assumptions are made which can be grouped into categories like:

- Thermodynamic State
- Thermo physical Properties and Material Properties
- Heat source, condenser and evaporator
- Heat and mass transfer

The heat and mass transfer models can be grouped into two types

- Non Rigorous Model which takes into account heat transfer but does not take into account mass transfer.
- Rigorous Model which solves the energy equation and the equation of motion simultaneously

Guilleminot et al. [36] presented a model to describe the heat transfer in a fixed bed of solid adsorbent in a finned reactor of rectangular cross-section.This model neglects the resistances to mass diffusion. This model uses finite-difference technique according to a Crank-Nicholson schema for simulation purposes. An experiment was conducted to validate this model, and the two heat transfer coefficients of the adsorbent bed and that of fins, were obtained by an identification technique. This uniform pressure model is more adapted to describe the history of solid adsorbent reactors used in thermal processes than uniform temperature models proposed by other authors. Boubakri*et al.* [37], simulated a model to calculate the operating performance of an adsorptive solar-poweredice-maker, and the model was validated experimentally. The model was an extension of the work performed in [36]. This model could estimate the limits of ice production by means of adsorptive collector-condenser technology. Using flat plate collectors the daily ice production reached about 11.5 kg per m^2 of collector and the corresponding COP was about 19%.

Fuller *et al.* [38] had presented a simple one-dimensional uniform pressure heat transfer model of a heat regenerative two-beds heat pump by taking into account heat transfer of the working fluid. The model is based on a two temperature approach which assumes that the adsorption pair, heat transfer fluid tube, and outer shell of the system, at a given space coordinate and time, are at the same temperature while the heat transfer fluid is at a different temperature. Zheng et al. [39] also performed similar simulations on a one-dimensional uniform pressure heat transfer model of a heat regenerative two-bed heat pump. The model being a three temperature model involves three energy balance equation *viz.* for the fluid, for the tube wall and for the adsorbent. The equations were solved using implicit difference method and the model was validated by the experimental results from other research works. Sun *et al.* [40][41][42] presented a model which was an extension of the model found in [39]. The diffusion term in the flow direction was included in the energy balance equation in the "three temperature" model. This model was used to investigate various aspects of the thermal wave heat-regeneration heat pump using iso-volumetric discretization. Sun *et al.* [43] further proved that iso-volumetric discretization is much more efficient than equal-spacing discretization. The effects of the thermal conductivity and the cycle time on the process were also presented. This model was further investigated by Pons and Feng [42] to investigate the effect of the number of transfer units (NTU) and the dimensionless outlet fluidtemperature at the end of the cold front in the adsorptive refrigeration cycles using thermal regeneration.

Szarzynski et al. [44] used the same model and performed three simulations:

- Adiabatic direct pressurization\depressurization with the condenser.
- Adiabatic internal vapour recovery between the adsorbers.
- Separation of the adsorber into separate compartmentsto avoid a heat pipe effect.

It was concluded that the first process significantly reduces the COP, while the second one enhances the cooling power,and the third one does not change the performance. In most of the above models, material thermo-physical properties are often assumed to be constant. However, this assumption is valid when the material undergoes small temperature changes and in the case of large temperature changes, possible errors may be done when using this assumption. Thus Pons and Szarzynski [45] performed analysis on this same model but by considering the continuity equation into the governing equations to account for the change of fluid velocity. Results obtained with the assumption of constant density and/or constant heat capacity was compared to those obtained with temperature dependent density andheat capacity. It was realized that the assumption on density had no influence on the COP, but, the temperature dependence of heat capacity could not be neglected.

Hajji and Khalloufi [46][47] presented a one-dimensional model which is almost the same as that of Guilleminot*et al.* [36], with certain modifications. They had simplified the

model by assuming the constant heating/cooling fluid temperature.The parametric analysis using this two-dimensional model revealed that a significant improvement of sorption kinetics can be obtained by reducing the distance between the fins and the contact resistance at the interface metal-adsorbent. Passo*et al.* [48] proposed a two-dimensional uniform pressure model similar to the one proposed by Guilleminot*et al.* [36]. LDF equation was additionally added to the model. The finite element method was used and the numerical solution was compared to experiments performedon a solar-powered icemaker. The model simulation was in agreement with the experimental results. It further stated that the overall solar COP could be improved by about 20% if one used the activated carbon AS instead of the active carbon AC-35. Alam [49] investigated a model using two-dimensional heat transfer equations one for the fluid side and the other for the adsorbent side. A parametric study was also conducted to show the effects of different non-dimensional parameters on the system performances andtheir results were similar to the results obtained from the literatures. Mhimid [50] established two numerical models for two-dimensional transient heatand mass transfer during water desorption by zeolite bed to study the validity of a thermal equilibrium assumption. The model was able to determine the time–space evolution of state variables such as temperature and moisture content. Finite Volume Method was used to solve the governing equations. The main advantage of this method is to ensure flux conservation, and thus avoid generation of parasitic sources.

Zhang et al. [51][52][53] proposed a three-dimensional heat and mass transfer numerical analysis model. This model included four sub-models: heat transfer in heating/cooling fluids, heat transfer in the metal tube, heat transfer in the fins,and heat and mass transfer in the adsorbent.A linear driving force (LDF) equation was introduced to account for mass transfer resistance and Darcy's law was used to determine vapor velocity in the porous media. Numerical results showed that the proposed model predicted the dynamic responseof the adsorption system well, compared with experimental data. It also gives a toolfor optimization of adsorption systems driven by solar heat or other low-grade heat.

IV. CONCLUSION

Thus it can be concluded from the above works that modeling analysis can be done in three ways: Thermodynamic model, lumped parameters model and Heat and Mass transfer model. Thermodynamic models are usually expressed in algebraic or relatively simple equations and are based on the steady state of the system. These models are useful in qualitative or semi-quantitative analysis of the system, and in general, theyare used to study the influence of temperature and heat transfer on system COP andspecific cooling power, for different adsorbent/adsorbate pairs. Lumped Parameters are generally considered to assess the transient nature of the model. Considering heat and mass transfer models, although much work hasn't been done on the mass transfer effects, possibly because of the complex nature of theadsorption process. These models are commonly expressed in partial differentialequations and can be used to find the most detail information. They serve as a designtool and are frequently used to study the effect of various geometric parameters,operating parameters on the system performance. Indeed, they are used to investigatethe validity of various assumptions.Model validation is a key step in model development since it offers the possibility of comparing computed results with actual system behavior. Experiments are mostlyused to validate the mathematical model. As such, there exists a large body of work to predict several features of the process. More effort is required before the models can be applied to optimal design of the systems, define actual operating conditions, aswell as to investigate further new closed adsorption cycles.

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