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DEVELOPMENT OF A NOVEL CIRCULATING FLUIDIZED ADSORPTION REFRIGERATION (CFAR) SYSTEM FOR CONTINUOUS OPERATION MODE: INTRODUCTION

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ABSTRACT

Adsorption cooling (refrigeration) technology offers the potential for energy savings and supports environmental sustainability, thereby meeting the current global regulations. In this study, a novel concept of a coconut-derived activated carbon-methanol adsorption refrigeration system, in which the circulation of the fluidized adsorbate-laden-solid desiccant (adsorbent) is achieved by means of a cyclone, is introduced. This work entails the design of the circulating fluidized adsorption refrigeration (CFAR) system with its components, its operation principle and its mathematical model formulations. The main design innovation considered in this work relates to the way in which the solid desiccant is circulated hermitically between the heat source and heat sink. Therefore, the concept of the configuration in this work with its pertinent potentials (which include continuous cold production, eradication of the issue of unnecessary load on the evaporator, maximum optimization of both adsorption and desorption processes due to the spatial separation of both desorber and adsorber, absence of thermal stress induction in the bed as heat source and heat sink heat exchangers are localised) is intended to overcome the bottlenecks often encountered by adsorption cooling technology thereby advancing it beyond the current niche market. Presentation of the detailed simulation results followed by the construction of a small scale prototype of the CFAR system for laboratory evaluation and testing are anticipated for future work.

Keywords: Adsorption-Desorption, Refrigeration, Fluidized, Solid desiccant, Cyclone.

1. INTRODUCTION

A large proportion of the people in developing countries live in remote locations where grid electricity coverage is sparse or unavailable. Cooling applications such as food and medicine preservation in such areas, therefore, requires alternative refrigeration system. Besides the merit of energy saving accredited to alternative energy sources, one of the essential targets of the SDGs is to completely abolish the non-renewable energy sources by 2030 and consequently achieving a reduction of CO_2 emissions. According to (Hamouda & Malek, 2006), there are 650g of CO_2 emitted for each kWh of electricity produced. The preserved amount of fossil fuel energy and CO_2 emissions when using a renewable energy powered-refrigeration system instead of an equivalent conventional vapour-compression freezer was estimated during the day by (Hadj Ammar, Benhaoua, & Bouras, 2017). Hence, renewable energy powered adsorption cooling technology has been the subject of extensive research for cooling applications due to its merits which are not limited to low energy intensity, use of low grade heat sources and being eco-friendly thereby meeting the current global regulations.

From the development history, adsorption refrigeration cycles, based on working principle, can be divided into two classifications which are basic or intermittent and advanced or continuous cycles. The basic cycles are the earliest ones which consist of simple and single-bed intermittent cycle mostly used in the solar powered refrigerator. In order to produce continuous refrigeration output, unlike in the case of the basic cycles whose refrigeration outputs are intermittent, the advanced cycles generally make use of two or more beds operating to achieve alternate cycles of adsorption and desorption.

Furthermore, going through the transitional development history as well as the study status of scholars globally, the advanced adsorption refrigeration cycles have been developed into: heat recovery cycle, heat and mass recovery cycle, thermal wave cycle, convective thermal wave cycle, cascaded cycle, multi bed and multi stage cycle, fluidised bed technology, constant temperature cycle and hybrid systems.

Hence, from the literature, it seems the performance of the basic cycle can no longer be significantly improved. Regarding the advanced cycles, although higher performances seemed to have been recorded about them, it can be noted that, in spite of the numberless attempts made by various researchers to improve their performances and as well maintain their presence in the market, they appears not yet ready to compete with the traditional vapour compression cooling systems due to identified technical and economic limitations like low COP, high initial cost, poor heat management, large volume and weight, operating conditional variations and automatic control which seem difficult to overcome. Honestly, most of the advanced cycles are just theoretically studied or on laboratory scale. They are often being limited by the issue of low COP and they usually require a continuously circulating cooling/heating medium and too many valves to operate uninterruptedly. However, the heat and mass recovery cycle is one of the easiest cycles used in practical applications. Therefore, the concept of the configuration in this work with its pertinent potentials (including continuous cold production, eradication of the issue of unnecessary load on the evaporator, maximum optimization of both adsorption and desorption processes due to the spatial separation of both desorber and adsorber, absence of thermal stress induction in the bed as heat source and heat sink heat exchangers are localised) is intended to overcome some of the above bottlenecks often encountered by adsorption cooling technology.

Hence, a novel circulating fluidised adsorption refrigeration (CFAR) system using G32-H, a coconut-derived activated carbon/methanol as working pair for continuous operation mode is introduced in this work. The objective of this present work is to only introduce the: design of the circulating fluidized adsorption refrigeration (CFAR) system with its allied components, its operation principle and its mathematical model formulations. Presentation of the detailed simulation results followed by the construction of a small scale prototype of the CFAR system for laboratory evaluation and testing are anticipated for future work.

2. OPERATION PRINCIPLE AND COMPONENTS OF THE CFAR SYSTEM

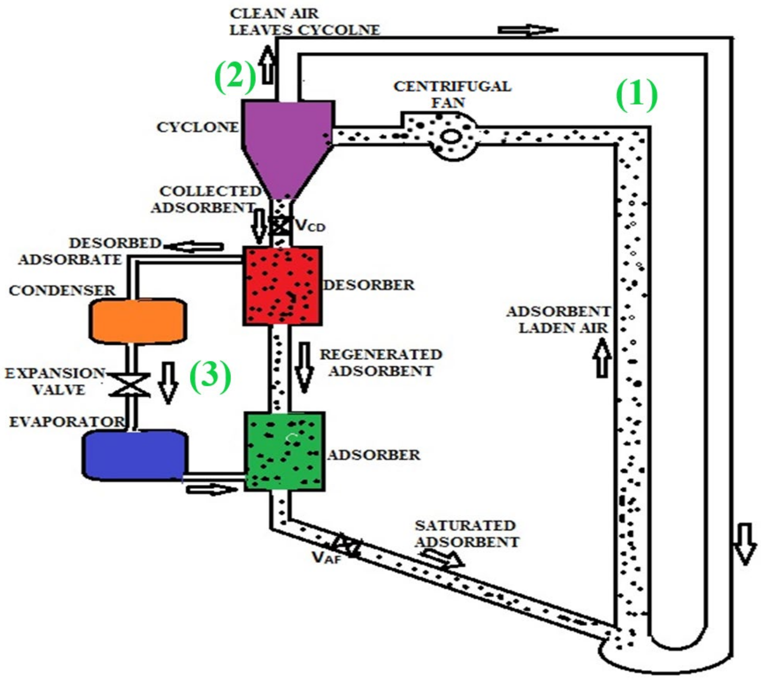

Figure 1 Schematic representation of the CFAR system

2.1 Operation Principle

The CFAR system as depicted in Figure 1 comprises three interconnected circuits that work in tandem. These circuits are: the circulatory circuit (CC) that involves a low-energy consumption centrifugal fan and circulating channels (pipes), (2) the separation circuit (SC) consisting of a reverse flow cyclone separator, and (3) the refrigeration circuit (RC) which includes a desorber/regenerator, a condenser, an evaporator, an adsorber, and two 1-way valves, V_{CD} and V_{AF}. As schematically represented in Figure 1, the adsorbent (already saturated with adsorbate) laden air stream, with the aid of the centrifugal fan, enters tangentially at the top of the cyclone barrel and travels downward into the lower (conical) part as it forms an outer vortex with increasing air velocity which results in a centrifugal effect on the adsorbent particles. Hence, the saturated adsorbent particles are separated from the air stream and enters into the desorber through the collection pipe (dip leg) while the clean air flows radially inwards to form the inner vortex and then flows out of the cyclone separator into the circulating field (pipe) to be laden again by the adsorbent. The saturated adsorbent enters into the desorber for the regeneration process. The progressive heating of the desorber consequently raises its pressure to that of the condenser, the point at which the desorber is connected to the condenser. Hence, this initiates desorption of the refrigerant vapour which is liquefied in the condenser. This process ends as the adsorbent reaches its maximum regeneration temperature and the adsorbate content reduces to the minimum value X_{min}. The regenerated adsorbent thereafter flows into the adsorber for the adsorption process. The high pressure liquid adsorbate leaves the condenser and enters through the expansion valve into the evaporator as a low pressure liquid adsorbate. As it gains heat energy from the load in the evaporator, it begins to boil and as soon as the adsorber pressure reaches the evaporator pressure, it then gets adsorbed by the adsorbent in the adsorber thereby producing cooling in the evaporator. The saturated adsorbent takes its course back into the flow path of the circulating air from the cyclone and then the mixture of the duo is extracted again by the fan into the cyclone to begin another cycle.

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2.2 CFAR System Novelties

The system configuration offers the following advantages: (i) It is a continuous process which can produce refrigeration continuously thereby overcoming the bottleneck of intermittent cold production associated with fixed beds. (ii) Once the system is started up, concentration and temperature profiles are formed and become time invariant, which simplifies the issue of unnecessary load on the evaporator as it is with fixed beds. (iii) In contrast to conventional fixed-bed adsorbers and other continuous systems in the literature, this system does not only stand out because of its continuous cold production, but also because adsorption and desorption processes occur separately (that is, they are separated spatially) and can thus be optimized maximally. (iv) The issue of switching between beds and the use of a reversible pump in the previous works is overcome here. Hence the valves complexity and thermal stress induced in the bed by switching between heating and cooling is completely solved. (v) Heat source and heat sink heat exchanger are localised.

2.3 Desiccant Circuit

As illustrated in Figure 2, the saturated desiccant takes its route from the cyclone into the desorber to undergo the regeneration/desorption process after which it enters the adsorber with reduced adsorbate content for the adsorption process. After the completion of the adsorption process, the saturated adsorbent enters with the aid of gravity into the circulatory channels and then get fluidized by the flow path of the clean air stream which is ready to be laden by it. Finally, with the aid of the centrifugal fan, it then enters into the cyclone to begin another cycle.

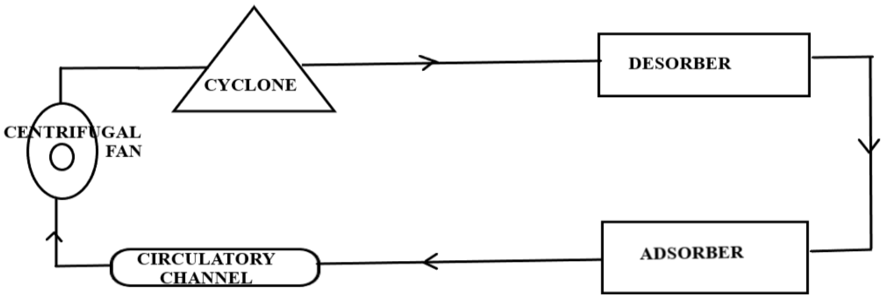

Figure 2 The schematic of the desiccant circuit

2.4 Refrigerant/Adsorbate Circuit

As illustrated in Figure 3, the circuit of the adsorbate starts from the desorber whose progressive heating initiates the desorption of the refrigerant vapour which then enters into the condenser to be liquefied. The high pressure liquid adsorbate leaves the condenser and then enters through the expansion valve into the evaporator as a low pressure liquid adsorbate which gains heat energy from the evaporator load. It begins boiling and then get finally adsorbed by the adsorbent in the adsorber thereby producing a cooling effect.

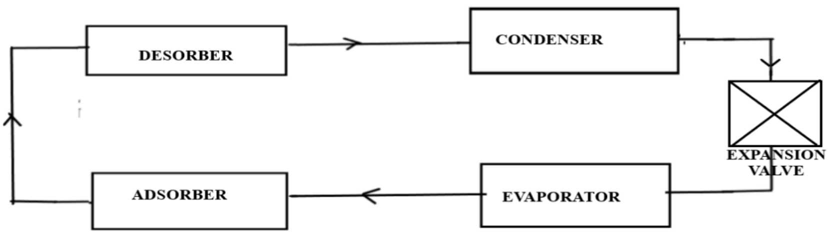

Figure 3 The schematic of the refrigerant circuit

2.5 Desiccant Separation

A gas-solid cyclone is introduced into the system to help separate the desiccant particles (already saturated with adsorbate) from the fluid stream by an induced centrifugal force (from a centrifugal fan) which is tangentially imparted on the wall of the cyclone cylinder. This force coupled with the density gradient between the fluid and the solid desiccant particles, increases the relative settling velocity of the solid desiccant particles and thereby driving them towards the cyclone wall where they slide to the particle exit and enter into the desorber through the collection pipe (dip leg) while the clean air flows radially inwards to form the inner vortex and then flows out of the cyclone separator into the circulating field (pipe) to be laden again by the desiccants particles. This vortex cyclonic separation is demonstrated in Figure 4 through a typical cyclone separator. The proposed cyclone separator is schematically represented in Figure 5. Details about it has been presented in our previous work (Oluleye & Boukhanouf, 2024).

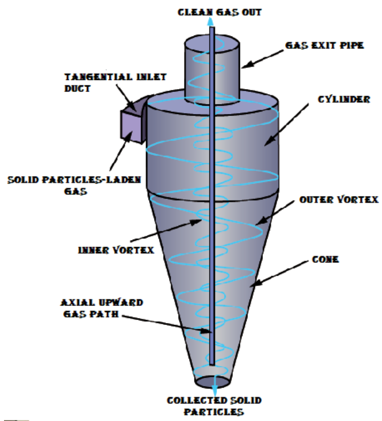

Figure 4 A typical cyclone separator (NPTEL)

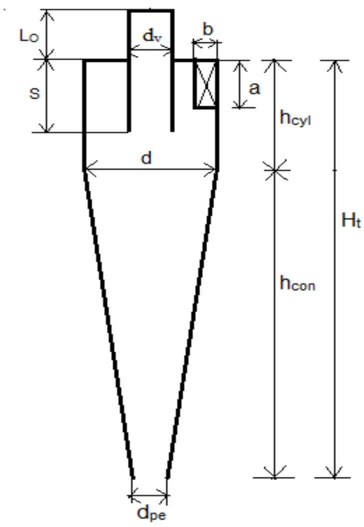

Figure 5 Schematic diagram of the proposed cyclone separator (Oluleye & Boukhanouf, 2024)

3.0 DESIGN AND MATHEMATICAL MODELLING OF THE PROPOSED CFAR SYSTEM CONFIGURATION

Detailed modelling of the novel design to investigate its performance parameters was carried out in two successive steps. The model formulation for the separation circuit cum the circulatory unit was first carried out and this was followed by that of the refrigeration (adsorption cooling/heating) unit. In determining the performance of the formal, a computer code was written using MATLAB software in order to determine the speed of adsorbent flow from the cyclone dipleg into the desorber inlet. All these and the allied results have been presented in our earlier work (Oluleye & Boukhanouf, 2024)**.** This present work is concerned with the mathematical formulations for the modelling of the heat and mass transfer of the adsorption cooling/heating circuit.

Mathematical modelling of the adsorption refrigeration system is highly important to give an overall representation of the system performance. The mathematical models which are generally used to simulate adsorption cooling system can be grouped into three, which are: lumped parameter model, heat and mass transfer model, and thermodynamic model (Bataineh & Taamneh, 2016; Pesaran, Lee, Hwang, Radermacher, & Chun, 2016; Teng, Leong, & Chakraborty, 2016; Yong & Sumathy, 2002). In order to dynamically study the adsorption circuit of the CFAR system, there is a need to model the adsorption kinetics, mass and energy balance within it. This is based on the heat and mass transfer (distributed parameter) model.
The following simplifying assumptions were applied to develop the model:
(a)The system is modeled as a one-dimensional system since the variation of the adsorbent temperature and the concentration is more dominant along the axial direction. (b)Hysteresis in the sorption isotherm, the heats of sorption and in the adsorbent flow are negligible. (c) Thermal and mass dispersion in the porous medium are negligible. (d)The transport of the adsorbate within the moving adsorbent due to capillary motion is negligible. (e)The gaseous adsorbate behaves as an ideal gas. (f)The speed and the mass flow rate of the adsorption pair stream are constant. (g)The temperature of the heating/cooling medium is constant and hence not modelled. (h)The local thermal equilibrium is satisfied, that is, the adsorbent and the adsorbate have the same temperature. (i)Adsorbent particles are homogeneous, isotropic and incompressible. (j)Convective mass transfer, heat losses due to radiation, viscous dissipation and the work done by pressure changes are neglected, and (k)The inlet condition of the adsorbent into adsorber is the same with its outlet condition from the desorber for any cycle in the system.
Based on the above assumptions, the isotherm, energy and mass balance equations are formulated as follows:

3.1 The Isotherm Equation

The equilibrium adsorption or desorption quantity at any state is determined by the Dubinin–Astakhov (D–A) equation (Hassan, Mohamad, & Al-Ansary, 2012; Wang, Wang, & Oliveira, 2009) as given below:

$$q(T,P) = q_o exp\left[-D\left(Tln\left(\frac{P_{sat}(T)}{P}\right)\right)^{n}\right] \quad \ldots 1$$

Where $P_{sat} = 133.33\exp\left(A - \frac{B}{(T+C)}\right)$ P_{sat} in Pascal and T in Kelvin as given by (Hadj Ammar et al., 2017). For the pair of activated carbon-methanol considered in this study, the above adsorptive properties according to (Qasem & El-Shaarawi, 2013), thermophysical properties as reported by (Mauran, Prades, & L'Haridon, 1993) and the values of A,B and C as given by (Bejan & Kraus, 2003) and (Reid, 1974)are all given in Table 1. Since this system is primarily aimed at solving energy problems in the rural countries of Africa, the reference-environment (ambient) conditions used in this work are set to the mean ambient conditions of Nigeria while the condenser and the evaporator pressures are set to a value which corresponds to the saturation temperature of T_C (condenser temperature) and T_E (evaporator temperature) respectively. T_C and T_E were chosen based on the general rule of thumb for an air-cooled condenser in a normal climate and for a cold room evaporator respectively with reference to the chosen ambient conditions.

3.2 Adsorber/Desorber configuration

The desorber/adsorber as shown in Figure 6 is basically of a cylindrical geometry which consists of an inner heat transfer tube containing the heating/cooling medium and an outer tubular shell which has a vapour mesh that serves as the outlet/inlet for the adsorbate vapour at one of its side. The radial space (R-r) between the duo along their length is filled with the moving solid adsorbent particles during their transit.

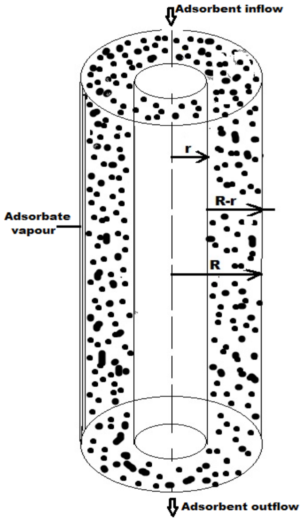

Figure 6 A schematic representation of the Desorber/Adsorber

Table 1 System and operating parameters for the adsorption refrigeration unit

Parameter	Symbol	Value	Unit
Specific heat of adsorbent	Cp_{sc}	920	J/kgK
Specific heat of adsorbate	Cp_{ads}	2534	J/kgK
Density of adsorbent	ρ_{sc}	370	kg/m^3
Ambient temperature	T_{amb}	26.9	℃
Condenser temperature	T_C	35	℃
Evaporator temperature	T_E	15	℃
Cooling temperature	T_L	30	℃
Heating temperature	T_H	100	℃
Latent heat of vaporization of adsorbate	L_v	1102×10^3	J/kg
Maximum adsorption capacity (G32-H)	q_0	0.38	kg/kg
Adsorption parameter	D	1.94×10^{-8}	K^{-1}
Adsorption parameter	n	2.59	
Adsorption parameter	A	18.587	
Adsorption parameter	B	3626.55	
Adsorption parameter	C	−34.29	
Desorption Time	$TimeMax_{des}$	120	s
Adsorption Time	$TimeMax_{ads}$	120	s
Height of adsorber/desorber	H	0.5	m
Thermal conductivity of adsorbent	k_{sc}	0.5	$\mathrm{W}m^{-1}K^{-1}$
Mass of adsorbent	M_{sc}	6	kg
Activation energy	E_a	40×10^3	J/mol
Universal gas constant	R	8.3145	$J/mol.K$
Pre-exponential coefficient of Arrrhenius equation	D_O	3.9×10^{-2}	m^2/s
Adsorbent porosity	ε	0.7	
Heat of sorption	H_S	1900×10^3	J/kg
Adsorbent flow velocity	u_{sc}	0.49	m/s

3.3 Energy Balance

Neglecting the convective heat transfer between the adsorbent and adsorbate, the energy balance for the adsorbent is:

$$\rho_{sc}\left(C_{P_{sc}} + qC_{P_{ads}}\right)\frac{\partial T_{sc}}{\partial t} + \bar{u}_{sc}\rho_{sc}\left(C_{P_{sc}} + qC_{P_{ads}}\right)\frac{\partial T_{sc}}{\partial z} = k_{sc}(1-\varepsilon)\frac{\partial^2 T_{sc}}{\partial z^2} + \rho_{sc}H_S\frac{\partial q}{\partial t} \ldots (2)$$

The first term on the left-hand side (LHS) of equation (2) represents the rate of internal energy change in the adsorption pair. The second term is the convective heat transfer term, that is, the spatial energy change in the adsorption pair due to flow in the axial direction. The first term on the right-hand side (RHS) stands for conduction heat fluxes due to inflow and outflow of adsorption pair which is the diffusion term. The last term on the RHS stands for the latent heat of desorption/adsorption which is proportional to the variation in the uptake/release of adsorbent vapour. This is known as the heat source term.

3.4 The Overall Mass Balance/Conservation

Neglecting the influence of the vapour velocity (external mass transfer resistance) for convective mass transfer on the mass change of the adsorbate, the following equation is arrived at for the mass balance.

$$\varepsilon\frac{\partial \rho_{ads}}{\partial t} + \bar{u}_{sc}\frac{\partial \rho_{ads}}{\partial z} + (1-\varepsilon)\rho_{sc}\frac{\partial q}{\partial t} = D_S\frac{\partial^2 \rho_{ads}}{\partial z^2} \ldots (3)$$

The effective diffusion coefficient, D_S, can be estimated from the Arrhenius equation: $D_S = D_O exp^{\left(\frac{-E_a}{RT}\right)}$. The first term on the LHS of equation 3 represents the temporal variation or accumulation in the adsorbate mass. The second term is the changes in its convective flow while the third term is the temporal adsorption changes, which is the rate of adsorption. The RHS term is the axial material flow which is the diffusion term. From the assumptions of local thermal equilibrium and the ideal gas, $\rho_{ads} = \frac{P_{ads}M_{ads}}{RT_{sc}}$ which if substituted into equation 3 gives equation 4 from which the variation of the adsorbate vapour pressure is estimated.

$$\frac{\varepsilon M_{ads}}{RT_{sc}}.\frac{\partial P_{ads}}{\partial t} + \frac{\bar{u}_{sc}M_{ads}}{RT_{sc}}.\frac{\partial P_{ads}}{\partial z} + (1-\varepsilon)\rho_{sc}\frac{\partial q}{\partial t} = \frac{D_S M_{ads}}{RT_{sc}} \ldots (4)$$

4. CONCLUSION

Introduced in this work is a novel circulating fluidised adsorption refrigeration (CFAR) system using G32-H, a coconut-derived activated carbon/methanol as working pair for continuous operation mode. The objective of this present work is to only introduce the: design of the circulating fluidized adsorption refrigeration (CFAR) system with its allied components, its operation principle and its mathematical model formulations. Detailed simulation results followed by the system development are anticipated for future work.

The main design innovation considered in this work relates to the way in which the solid desiccant is separated and fluidised with the aid of a gas-solid cyclone and then circulated hermitically between the heat source and heat sink. Therefore, the concept of the configuration in this work with its pertinent potentials (which include continuous cold production, eradication of the issue of unnecessary load on the evaporator, maximum optimization of both adsorption and desorption processes due to the spatial separation of both desorber and adsorber, absence of thermal stress induction in the bed as heat source and heat sink heat exchangers are localised)

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