Performance Investigation of Rotary Desiccant Wheel by Mathematical Modeling using Mathematica

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Abstract : Desiccant cooling is an environment friendly air conditioning system used as a option to conventional vapor compression system. In this system, desiccant wheel is an important component in which dehumidification takes place by means of adsorption process. Appropriate design of desiccant wheel is necessary to fulfill the requirement of this system to make it efficient. Performance investigation of desiccant wheel can be obtained by analysis of air passing through the same in terms of temperature and humidity ratio. Analysis with different parameter is necessary for appropriate design and optimization of desiccant wheel to achieve better dehumidification in ambient as well as room temperature. Here Mathematical Modeling is used to evaluate the temperature and humidity using Mathematica software. Validation is carried out by using Experimental setup.

***Index Terms* - Desiccant wheel, Dehumidification, Numerical Analysis, Mathematical modeling**

I. INTRODUCTION

As shown in Fig 2.1[1] there is layout of desiccant cooling system. Principle behind the cooling system is *chemical adsorption and desorption process*. In this layout there is three process unit that are dehumidification unit, regeneration unit and cooling unit.

1. Dehumidification unit

It is also known as process unit where dehumidification takes place by the desiccant material which has high affinity to moisture and also there is a pressure difference in desiccant material and inlet air (as per Dalton's law). When ambient air is supplied to the dehumidifier there is many parallel passage from which air is passed where a layer of desiccant is provided.

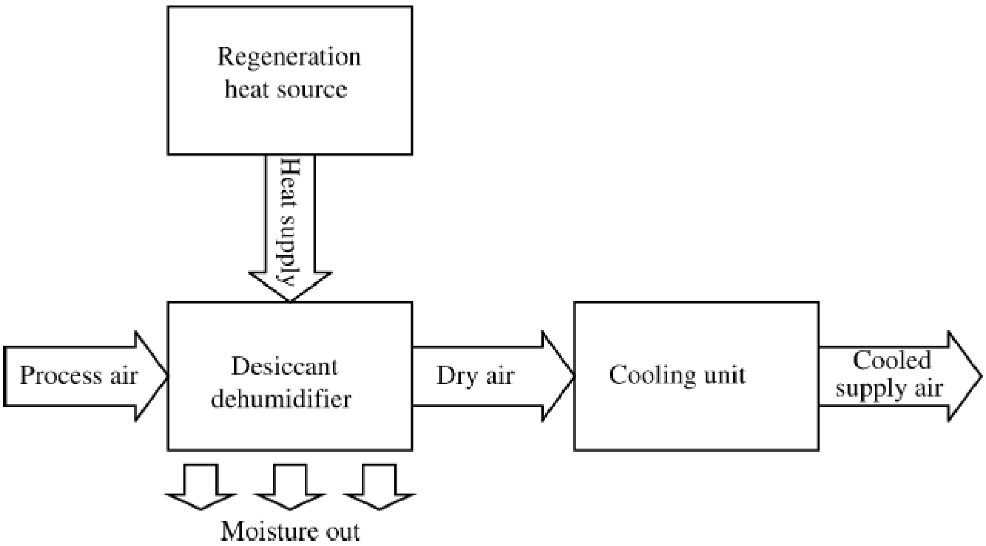

Fig. 1 layout for Principle of desiccant cooling system

2. Regeneration unit

After removal of moisture in desiccant dehumidifier there will be desiccant material which is fully saturated with moisture, so removing of moisture from the desiccant material is necessary. So the process to remove moisture from desiccant material that is to regenerate the dehumidifier again for the dehumidification process is known as regeneration process. It can be carried out by suppling the hot regeneration air from the regenerative heat source.

3. Cooling unit

The cooling unit is either a traditional evaporater or a cooling evaporating coil in which cooling process takes place from where cooled air is supplied to the room. The main role of the unit is to handle the sensible load while desiccant material layer removes the latent load.

II. RESEARCH METHODOLOGY

Mathematical Modeling Method

In this method there is a two steps followed

1. To derive Governing Equations
2. To solve the equations

1. To derive governing equations

This is a step in which governing equations are derived with the consideration of process takes place. Here dehumidification and temperature rise takes place in dehumidifier so euations will be in two forms

a. Mass Balance(in terms of humidity)

b. Energy Balance(in terms of temperature)

2. To solve the equations

This steps includes defining the initial and boundary conditions and the another is to select the mathematical method to solve them.

In the CFD analysis, mass and energy balance is the basis

Energy balance equation[2]

$$\frac{\partial T_a}{\partial t}+u\frac{\partial T_a}{\partial x}=\frac{4h}{D_h c_{pa}}(T_a-T_d) \quad (1)$$

Mass balance equation[2]

$$\frac{\partial Y_a}{\partial t}+u\frac{\partial Y_a}{\partial x}=\frac{4h_m}{D_h}(Y_a-Y_d) \quad (2)$$

$\rho_a = 1.207 kg/m^3$

$\rho_d = 720 kg/m^3$

$T_d = 30°c$

$Y_d = 0.0007 kg/kg$

$u = 3 m/s$

$C_{pg} = 1.009*10^3 J/kgK$

$h = 45.01 W/m^2K$ [2]

$h_m = 4.1*10^{-10} m^2/s$ [3]

Sinusoidal Geometry

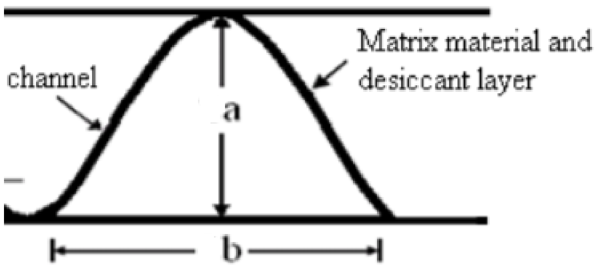

Fig. 2 Sinusoidal Geometry

$$P = 2b + 2\sqrt{a^2\pi^2 + b^2}\,\frac{3+\left(\frac{2b}{a\pi}\right)^2}{4+\left(\frac{2b}{a\pi}\right)^2} \text{ [11]}$$

$$A = 2ab = 8.1*10^{-5}\,m^2 \text{ [11]}$$

Sinusoidal Geometry (a:b=1:2)

$$a = 4.5*10^{-3}\,m$$

$$b = 9*10^{-3}\,m$$

$$P = 4.55*10^{-2}\,m$$

$$D_h = \frac{A}{P} = \frac{8.1*10^{-5}}{4.55*10^{-2}} = 1.78*10^{-3}\,m$$

From eq. (2)

$$\frac{\partial Y_a}{\partial t} + 3\frac{\partial Y_a}{\partial x} = \frac{4*4.1*10^{-10}}{1.78*10^{-3}}(Y_a - 0.0007)$$

$$\frac{\partial Y_a}{\partial t} + 3\frac{\partial Y_a}{\partial x} = 9.21*10^{-7}(Y_a - 0.0007)$$

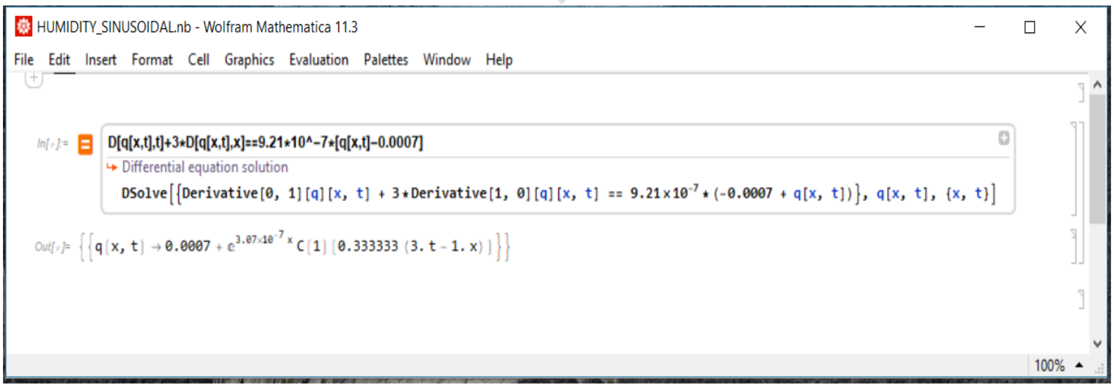

Fig. 3 Humidity solution of Sinusoidal geometry(1:2) in Mathematica

Simplifying the above equation,

$$Y[x,t] = 0.0007 + C_1 e^{3.07*10^{-7}x}\{t - x/3\}$$

Applying boundary conditions,

$$Y[0,t] = Y_{process} = 0.017$$

$$0.017 = 0.0007 + C_1 t$$

$$C_1 t = 0.0163 \qquad (3)$$

$$Y[l,t] = Y_{regeneration} = 0.0008$$

$$0.0008 = 0.0007 + C_1 e^{3.07*10^{-7}} \{t - 0.1/3\}$$

Taking value from eq. (3),

$$C_1 = 4.85*10^{-4}$$

$$Y[x,t] = 0.0007 + 4.85*10^{-4} e^{3.07*10^{-7} x} \{t - x/3\}$$

at the point x=0.1m and t=25

Y[0.1,25]=0.0128

From eq.(1),

$$\frac{\partial T_a}{\partial t} + 3\frac{\partial T_a}{\partial x} = \frac{4*45.01}{1.78*10^{-3}*1.009*10^{3}}(T_a - 30)$$

$$\frac{\partial T_a}{\partial t} + 3\frac{\partial T_a}{\partial x} = 100.24(T_a - 30)$$

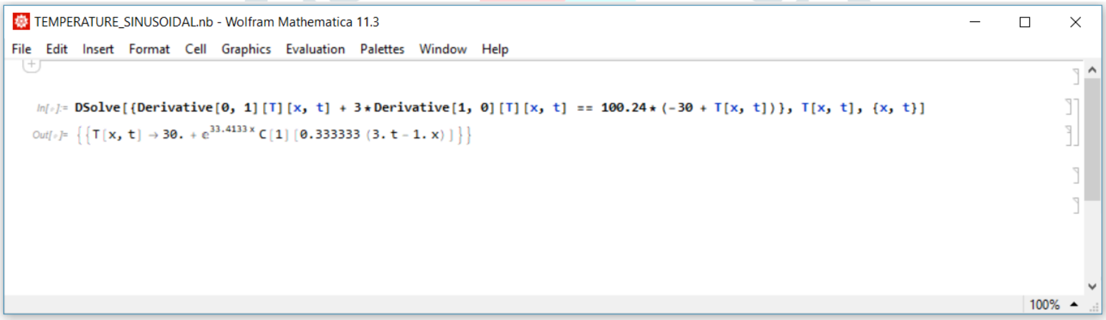

Fig. 4 Temperature solution of Sinusoidal geometry(1:2) in Mathematica

Simplifying the above equation,

$$T[x,t] = 30 + C_2 e^{33.4133x} \{t - x/3\}$$

Applying boundary condition,

$$T[0,t] = T_{process} = 35°c$$

$$35 = 30 + C_2 t$$

$$C_2 t = 5 \qquad (4)$$

$$T[l,t] = T_{regeneration} = 80°c$$

$$80 = 30 + C_2 e^{33.4133*0.1} \{t - 0.1/3\}$$

Taking value from eq. (4),

$$C_2 = 0.03$$

$$T[x,t] = 30 + 0.03e^{33.4133x}\{t - x/3\}$$

at the point x=0.1m and t=25

T[0.1,25]=51.23°C

Table 1 Summery of Mathematical Result

	D_h, (m)	$T_{a(inlet)}$ (°C)	$T_{a(outlet)}$ (°C)	% increment	$Y_{a(inlet)}$ (kg/kg)	$Y_{a(outlet)}$ (kg/kg)	% decrement
Sinusoidal(1:2)	$1.78*10^{-3}$	35	51.23	46.37	0.017	0.0128	24.71
Sinusoidal(1:1)	$1.80*10^{-3}$	35	52.43	49.8	0.017	0.0133	21.76

Experimental Setup

Fig. 6 shows the setup of the desiccant dehumidification system in which there is aasembly of desiccant dehumidifier with the fan for supplying the air with velocity to pass into the channel of the wheel.

Fig. 5 Experimental Setup

Here, Sinusoidal Geometry(1:1) is in the experimental setup as shown in Fig. 6

Fig. 6 Desiccant Wheel having Sinusoidal Geometry(1:1)

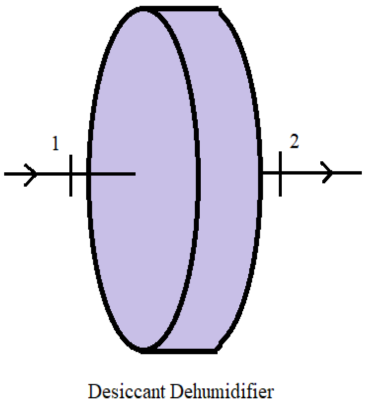

Fig. 7 Desiccant dehumidifier with state points

Here, there is a state point 1 and 2 shows the inlet and outlet of the desiccant dehumidifier. Table 8.2 shows the result in terms of temperature and humidity in experimental setup at both the point.

Table 2 Result from experimental setup

	Temperature (°C)		% increment	Humidity (kg/kg)		% decrement
	Point 1	Point 2		Point 1	Point 2	
1st	34	53.15	56.32	0.012	0.008	33.33
2nd	39	59.83	53.41	0.016	0.011	31.25

III. RESULTS AND DISCUSSION

Comparison of result with Narayan et. Al.[2]

As per the result shown in Table 1, there is a result of sinusoidal geometry. Narayan has taken Sinusoidal (1:2) geometry in his research work. Comparison of his study and current study can be shown in Table 3

Table 3 Comparison between result of Narayan et. Al. and Current Study

	$T_{a(in)}$ (°C)	$T_{a(out)}$ (°C)	% increment	$Y_{a(in)}$ (kg/kg)	$Y_{a(out)}$ (kg/kg)	% decrement
Narayan et al.	29.7	47.32	59.32	0.018	0.0135	25.00
Current Study	35	51.23	46.37	0.017	0.0128	24.72
Current Study	42	61.19	45.69	0.019	0.0141	25.71
Current Study	49	70.69	44.26	0.021	0.0158	24.76

Here as shown in Table 3, there is a increment in temperature of air after passing through desiccant dehumidifier. The average increment in temperature in the current study is & Narayan et al[2] is 45.44% & 59.32%.

Here as shown in Table 3, there is a decrement in humidity of air after passing through desiccant dehumidifier. The average decrement in humidity in the current study is & Narayan et al[2] is 25.06% & 25%.

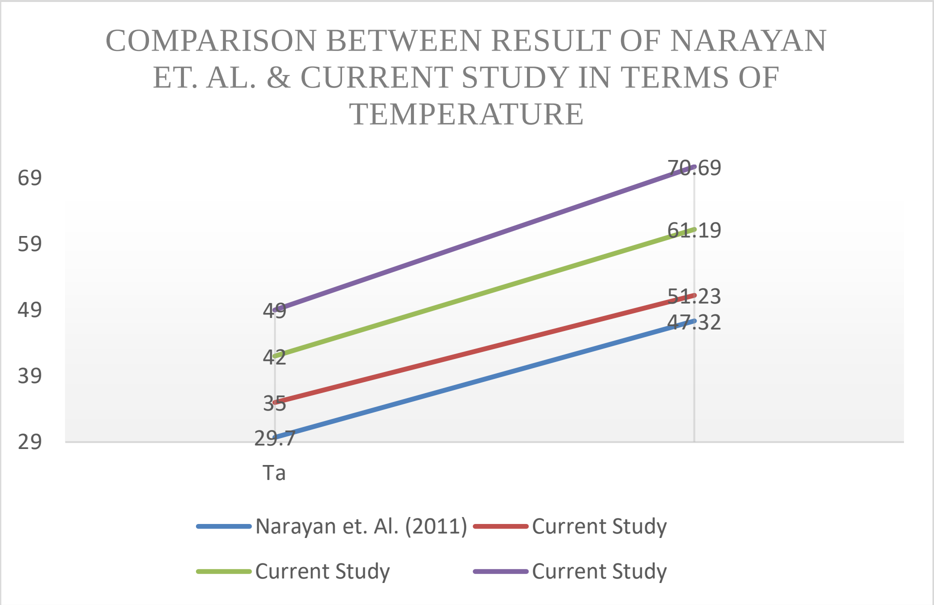

Fig. 8 Comparison of temperature result with Narayan et. Al.

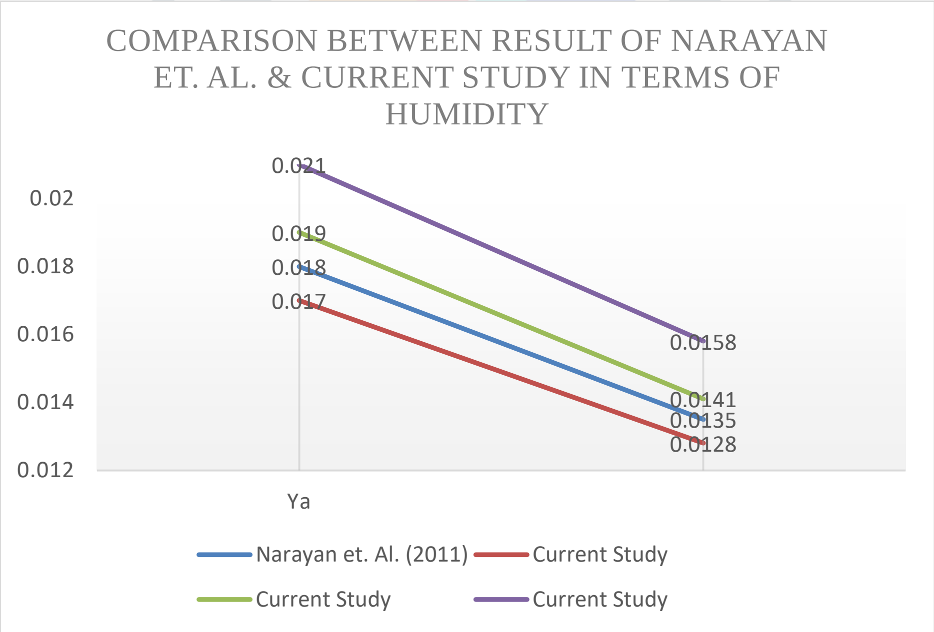

Fig. 9 Comparison of humidity result with Narayan et. Al.

Validation by Experimental Setup

Here as shown in Table 3, there is a increment in temperature of air after passing through desiccant dehumidifier. The average increment in temperature in the current study is & Experimental setup is 45.44% & 54.865%.

Here as shown in Table 3, there is a decrement in humidity of air after passing through desiccant dehumidifier. The average decrement in humidity in the current study is & Experimental setup is 25.06% & 32.29%.

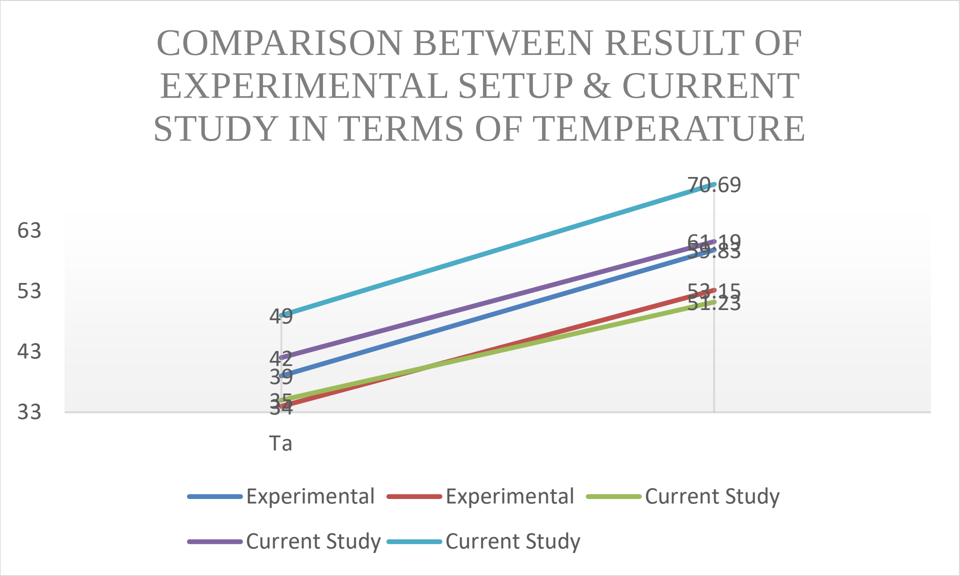

Fig. 10 Comparison between result of Experimental setup & Current study in terms of temperature

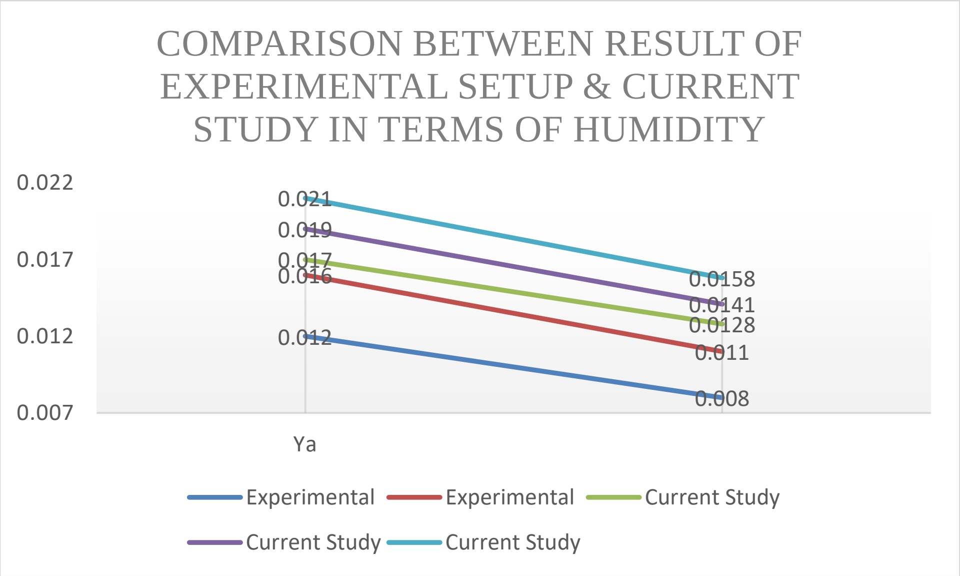

Fig. 11 Comparison between result of Experimental setup & Current study in terms of humidity

IV. CONCLUSION

Dehumidifier performance depends on the outdoor condition, speed of desiccant wheel, regeneration temperature, desiccant material, channel geometry, etc. It is found that the good performance can be achieved in hot and humid environment, that is outdoor condition affects the performance of the desiccant dehumidification system. Channel geometry affects in the performance of desiccant dehumidifier. Sinusoidal geometry is the best and the next are triangular and rectangular(square) geometry. Desiccant material with the consideration of moisture removal rate and regeneration temperature is chosen in the system for the optimum performance. So the different parameters discussed above affect the whole performance of the dehumidifier.

NOMENCLATURE

Y	Humidification Ratio (kg/kg)
c	specific heat (J/kg K)
c_p	constant pressure specific heat (J/kg K)

T	Temperature (K)
x	axial direction
t	time (s)
m	mass (kg)
h_{fg}	Latent heat of water vapor (J/kg)
h_m	convective mass transfer coefficient (kg/m^2 s)
h	convective heat transfer coefficient (W/m^2 K)
P_p	perimeter of channel (m)
D_h	hydraulic diameter of the channel (m)
A	cross-section of channel (m^2)
W	water content of desiccant ($kg_{adsorbate}/kg_{adsorbent}$)
D_k	Knudsen diffusivity (m^2 /s)
D_o	Ordinary diffusivity/molecular diffusivity (m^2 /s)
D_S	Surface diffusivity (m^2 /s)
A_r	Area ratio of air flow passage to the total area of one channel (m^2)
Nu	Nusselt number
u	Velocity (m/s)
k	Thermal conductivity (W/mK)
q_{ad}	heat of adsorption (J/kg)
f	Friction factor
P_s	Saturated Pressure (Pa)
P	Pressure (Pa)
Re	Reynold Number
Y_e	equilibrium specific humidity of air at adsorbent surface (kg_{water} / kg_{air})
N	revolution of desiccant wheel per hour
f_m	mass fraction of desiccant wheel
RH	Relative humidity

GREEK WORDS

ϕ	Volume ratio of desiccant material in layer
ε	Porosity
δ	Thickness of channel wall (m)
λ	half of height of channel (m)
ρ	Density (kg/m^3)

SUBSCRIPTS

a	Air
d	Desiccant
da	Dry air
in	Inlet
m	Matrix material
out	Outlet
p	Process air
r	Regeneration air
v	Water vapor
l	liquid
w	wheel
e	equilibrium state

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