SECOND LAW ASSESSMENT FOR AN ANNULAR SENSIBLE HEAT THERMAL ENERGY STORAGE UNIT

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الملخص

تهدف هذه الورقة إلى تقييم أداء وحدة لتخزين الطاقة الحرارية من منظور القانون الثاني للديناميكا الحرارية، حيث استخدمت تقنية الحجوم المحدودة للتحليل العددي. تم إعداد برنامج حاسوب بلغة الفورتران لمحاكاة وحدة التخزين الحراري التي تتكون من اسطوانتين مفرغتين بقطرين مختلفين وبمحورين منطبقين. وُضِعت مادة التخزين في الفراغ بين الأسطوانتين وعُزِل السطح الخارجي للوحدة، بينما عُرِّض السطح الداخلي لتبادل حراري بالحمل مع هواء متدفق. أُستُخدِم نوعين من مواد التخزين الحراري وهما الحديد الزهر والطوب الحراري، وتم حساب الأنتروبي المتولدة وكذلك اللاإنعكاسية. وُجد أنه أثناء الفترة العابرة، يكون التخزين الحراري واللاإنعكاسية في مادة الحديد الزهر أعلى من ذلك في مادة الطوب الحراري، إلا إن هذا الإختلاف في الأداء الديناميكي الحراري يتناقص مع الاقتراب من حالة الإستقرار.

ABSTRACT

This paper explores numerically the internal entropy generation and hence the internal irreversibility for an annular sensible heat thermal energy storage unit. Finite volume technique is adopted for the analysis with fully implicit numerical technique. A storage unit composed of two horizontal concentric cylinders with different diameters is considered for the analysis. The space between the two cylinders is filled with the storage material. Two different materials with different thermal diffusivities are considered for the analysis; those are cast iron and brick. The outside surface of the storage unit is insulated, while the inside surface exchanges heat by convection with air. The only mode of heat transfer inside the storage material is the heat transfer by conduction. The problem is a two-dimensional one. It is found that during the transient period, both the storage capacity and the internal entropy generation in cast iron are substantially higher than those in brick. However, as the steady state condition is approached with the increase in charging time, the discrepancies in the thermodynamic performance between the two storage materials are reduced.

KEYWORDS: Thermal Storage Units; Entropy Generation; Irreversibility; Thermal Diffusivity

INTRODUCTION

Energy storage can reduce the time or rate mismatch between energy supply and energy demand, and it plays an important role in energy conservation. Different methods for Thermal Energy Storage (TES) are defined and discussed; sensible (air, water, and underground thermal energy storage), latent (with phase change materials), and thermo-chemical (chemical reactions and absorption systems) energy storage [1]. The application of Thermal Energy Storage systems can provide very good advantages for customers and electric utilities, where it can shift peak electric load to off-peak time, this will reduce costs by storing hot temperature energy for later use. Perhaps the most promising application of thermal energy storage is for solar heated structures, and almost any material can be used for thermal energy storage [2]. Exergy concept is adopted for simulation and performance evaluation of storage units. Dincer [3] reported the linkages between energy and exergy and he highlighted the importance of the exergy and its essential utilization in numerous ways. Z. Rant in 1956 introduced the new word "exergy" to express the quality of energy [4]. The degradation in exergy can be expressed by Gouy- Stadola law. Exergy destruction for a certain process is evaluated by the product of the sum of entropy increase $\Sigma\Delta S$ of all the bodies taking part in the process, and the reference temperature [5]. Bejan [6,7] introduced the concept of entropy generation units as the means for evaluating the performance of heat exchangers. Saborio et al. [8] made an extension to the irreversibility minimization analysis applied to heat exchangers to include a term accounts for the exergy of the material of construction of the heat exchanger. They claim their analysis provides more realistic results. Bejan [9-11] presented a treatment of a simple sensible heat thermal energy storage unit. The analysis was based on the lump system of analysis and indicated the existence of two thermodynamic optima in designing sensible storage unit. The first, an optimum charging time beyond which the loss in exergy associated with steadily discharging gas into the atmosphere becomes dominant. The second, an optimum number of heat transfer units above which the loss of exergy due to friction in the working fluid side becomes dominant. His analysis was limited to a process of charging only, and pointed out thermal energy; to be stored at the instance of maximum second law efficiency is only 50% to 70% of the maximum energy storage capability. The state-of-the-art and the application of exergy concept in the evaluation of the performance of thermal energy storage units is explored by Roman Domanski and Giuma Fellah [12]. Exergy analysis for the evaluation of a thermal storage system employing phase change materials with different melting temperatures is introduced by Roman Domanski and Giuma Fellah [13]. It is concluded that the second law efficiency can be improved by employing more than one storage unit connected in series, and the downstream storage temperature should be close to the environment temperature. Storing thermal energy for later use is a vital issue from economic point of view. In the present work, a sensible heat storage unit of an annular configuration is to be modeled, simulated and evaluated from thermodynamic point of view.

MATHIMATICAL MODEL

A storage unit which is composed of two horizontal concentric cylinders with different diameters is considered for the analysis. The current configuration is adopted for the analysis due to its compactness and reliability. The space between the two cylinders is filled with the storage material as shown Figure (1). The inside diameter of the storage unit is D_i, and the outside diameter is D_o, the unit length is L, the outside surface is insulated, while the inside surface exchanges heat by convection with a flowing air. The only mode of heat transfer inside the storage material is the heat transfer by conduction. The problem is a two dimensional one. The entropy generation within the storage material is to be determined.

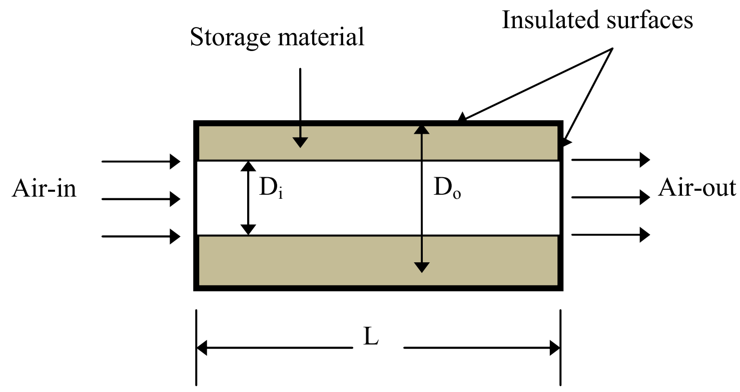

Figure 1: Thermal energy storage unit

The temperature distribution inside the storage material is governed by the energy equation. The outer surface and both ends are insulated. The problem is modeled as a heat transfer problem in a two dimensional, cylindrical- coordinate in the radial and axial directions.

The governing equations:

For the solid material ($r_i \leq r \leq r_o$), the two dimensional-transient heat conduction equation is given by:

$$\rho c_P \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \tag{1}$$

Where T is function in t, r and z.
The initial Condition is written for the whole region as:
At $t = 0$; $T = T_{initial}$.
The adiabatic boundary conditions at the outer surface ($r = r_o$), and at the ends of the storage unit are:

$$\frac{\partial T}{\partial r} = 0 \text{ at } r = r_o \text{ and } 0 \leq z \leq L \tag{2}$$

$$\frac{\partial T}{\partial z} = 0 \text{ at } z = 0 \text{ and } r_i \leq r \leq r_o \tag{3}$$

$$\frac{\partial T}{\partial z} = 0 \text{ at } z = L \text{ and } r_i \leq r \leq r_o \tag{4}$$

And for the inner surface ($r = r_i$):

$$k\frac{\partial T}{\partial r} = h\left(T_{fluid} - T_i\right) \text{ at } r = r_i \text{ and } 0 \leq z \leq L \tag{5}$$

The Entropy Generation

For two dimensional-cylindrical coordinates, the local entropy generation rate per unit volume within a solid material is [10]:

$$\dot{S}'''_{gen} = \frac{k}{T^2}\left[\left(\frac{\partial T}{\partial r}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] \quad (6)$$

The rate of entropy generation over the entire volume ($\dot{S}_{gen}$) can be calculated as follows:

$$\dot{S}_{gen} = \oint_V \dot{S}'''_{gen} \partial r \partial z \quad (7)$$

The integration of the entropy generation rate over the entire charging time from t_1 to t_2 gives the total entropy generation (S_{gen}) as:

$$S_{gen} = \int_{t_1}^{t_2} \dot{S}_{gen} \partial t \quad (8)$$

The total irreversibility (I) is then calculated as:

$$I = T_0 S_{gen} \quad (9)$$

ASSUMPTIONS FOR THE ANALYSIS

A reliable size of the storage unit is selected for the simulation. A practical inlet temperature which is close to the exhaust temperature of the steam power plant, and the standard ambient temperature are also selected for the analysis. The initial temperature is selected slightly different from the environmental temperature just to initiate the numerical calculations. A suitable speed for the working fluid which is assumed to have the properties of air is selected. The adopted parameters for the simulation are tabulated in Table (1). Table (2) shows the properties of the cast iron and bricks.

Table 1: Adopted parameters for the analysis

L (m)	D_o (m)	D_i (m)	$T_{initial}$ (^oC)	T_{inlet} (^oC)	u (m/s)	T_0 (^oC)
1.0	0.5	0.25	24	135	0.2	25

Table 2: Properties of Cast Iron and Bricks

	ρ (kg/m^3)	c_P (J/kg.K)	k (W/m.K),	α (m^2/s)
Cast Iron	7920	450	55	138E-7
Bricks:	1698	840	0.69	4.84E-7

VALIDATION OF THE MODEL

To validate the present mathematical model, the model is checked against other numerical results for two dimensional of a hollow cylinder. The current results are compared with that presented by Marco Donisete de Campos [14]. The obtained results from literature together with that calculated by the current model are presented in

Figure (2) for Fourier numbers (Fo) 0.1, 0.2, and 0.5. Here $r^* = \frac{r}{r_o}$, and $\theta = \frac{T(r,t) - T_0}{T_{initial} - T_0}$,

Good agreement is found.

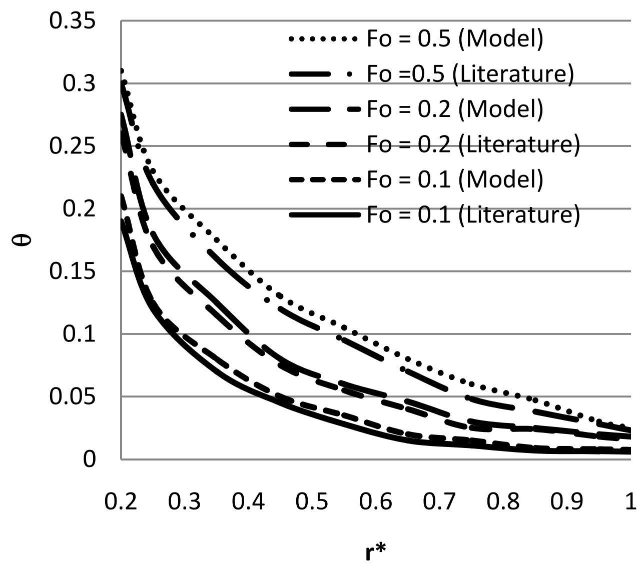

Figure 2: Validation of the present model

RESULTES AND DISSCUTION

The effect of thermal diffusivities on the temperature distribution and hence on the entropy generation during the transient period of the heat transfer is substantial. The thermal diffusivity of cast iron is about 28.51 times of that of the brick, see Table (2). To look at the effect of thermal diffusivity on the temperature distribution during the transient period, the temperature variations with time for three points located on the inner, intermediate and outer surfaces in the middle of the storage unit are shown in Figure (3) for cast iron and Figure (4) for brick.

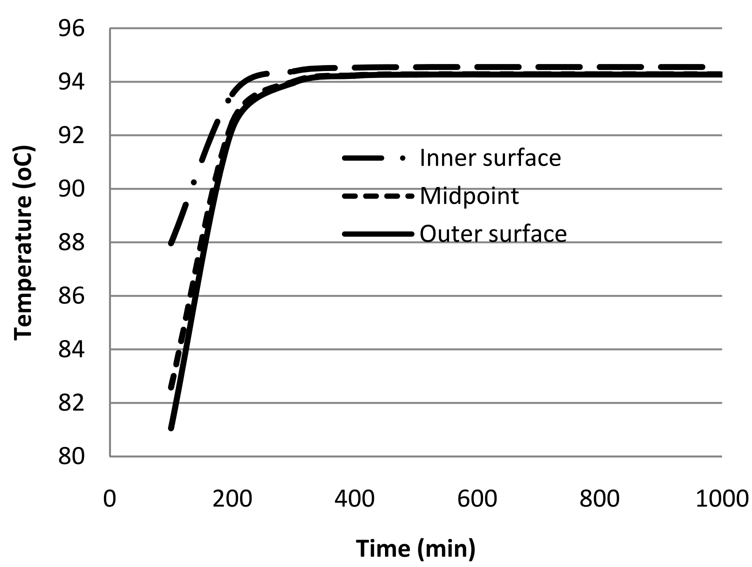

Figure 3: Variation of temperature with time for cast iron in the middle of the storage unit

Since the speed of heat propagation into solid material increases with the increase in thermal diffusivity, it can be seen that for the same period of time, cast iron reaches higher temperature, and attains steady state condition faster than brick.

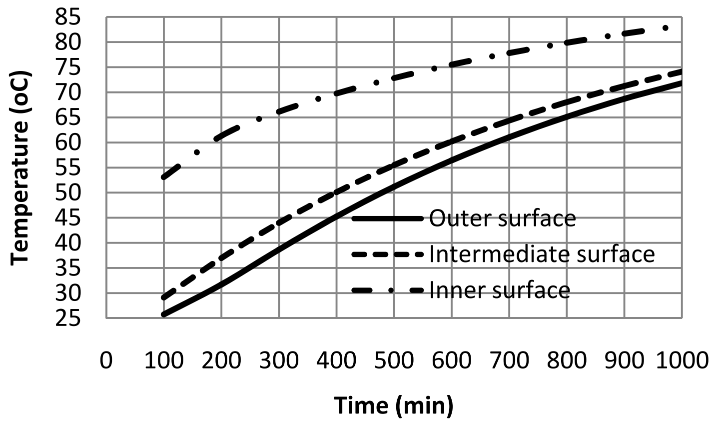

Figure 4: Variation of temperature with time for brick in the middle of the storage unit

The significant differences in temperature distribution between cast iron and brick would certainly affect the amount of entropy generation and hence the irreversibility for the two storage materials. Thermal diffusivity is interpreted as the ratio of the energy transported and energy stored within the storage material. It can be seen that the tendency of the cast iron to reach a uniform temperature distribution is larger than that for the brick. As the temperature within the storage material approaches uniform state instantaneously, the entropy generation reaches its maximum value. Figure (5) shows the variation of temperature gradient (dT/dr) for the cast iron unit with temperature (T) at the middle of the inner surface of the storage unit. Due to relatively large thermal diffusivity, there is a fast transfer of heat, and hence, the temperature gradient is a maximum at the beginning of the charging process, and then decreases with the increase in temperature and so with time as the temperature distribution becomes more uniform.

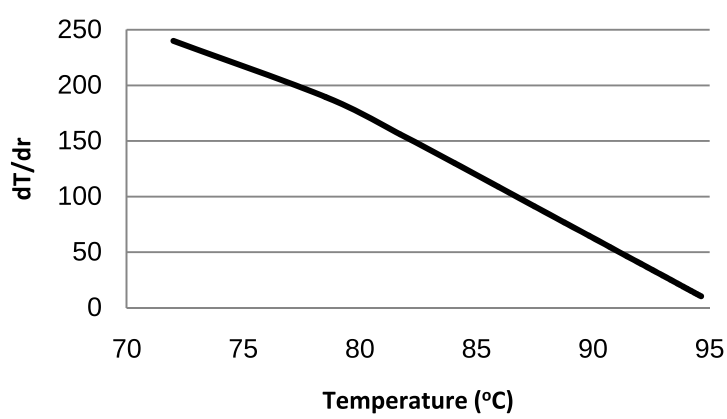

Figure 5: Variation of temperature gradient with temperature for cast iron

The effect of temperature gradient behavior for cast iron on the entropy generation can be explained by looking at equation (6). It can be seen that for a given thermal conductivity, the entropy generation is affected by temperature gradient, and temperature of the storage material. An increase of the storage temperature and a decrease of the temperature gradient with time, cause a reduction in entropy generation with time as shown in Figure (6). A sharp decrease in entropy generation during the first 100 minutes of charging time is found. This approach is in consistency with the steady state approach as shown in Figure (3), and with the sharp decrease in temperature gradient as shown in Figure (5).

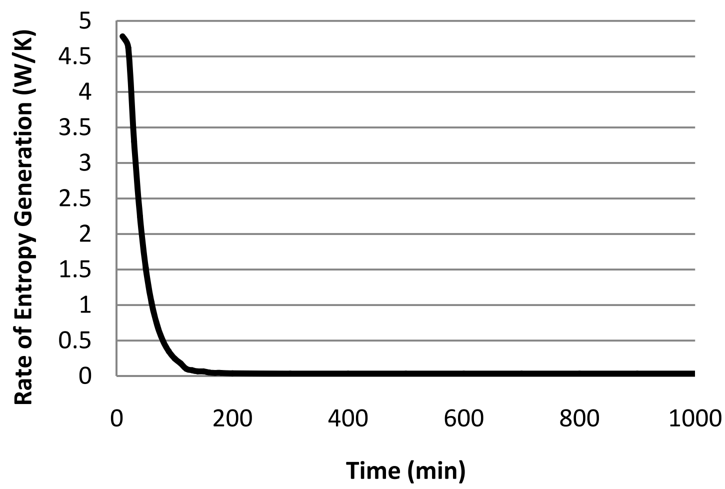

Figure 6: Variation of rate of entropy generation with time for cast iron

Figure (7) shows the variation of temperature gradient (dT/dr) with temperature (T) for brick. The effect of relatively low thermal diffusivity is dominant up to a certain point during which the temperature gradient increases with the increase in temperature (and hence with charging time). After which the material temperature becomes more uniform and a reduction in temperature gradient occurs. The behavior of the temperature gradient as explained would cause an increase and then a decrease in the entropy generation as shown in Figure (8).

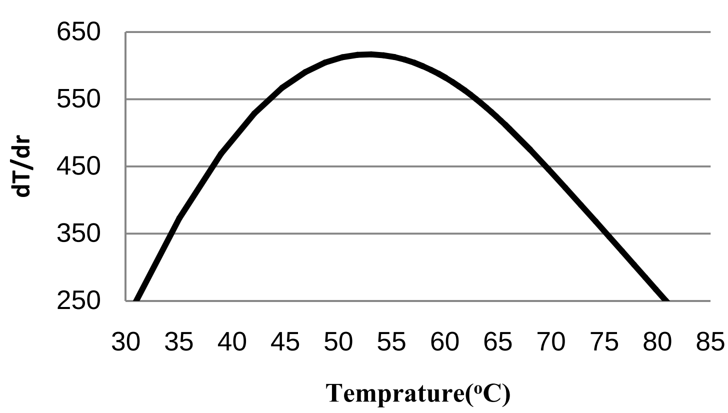

Figure 7: Variation of temperature gradient with temperature for brick

The total entropy generation is estimated by calculating areas under the entropy-time curves. The total entropy generation, irreversibility and stored energy are tabulated in Table (3) for charging time of 100 and 1000 minutes. It can be seen that both internal irreversibility and the amount of stored energy are larger in the cast iron unit, and increase with the increase in charging time. For cast iron, it can be seen that 82.1% of the total entropy generation occurs during the first 100 minutes, this is due relatively large diffusivity, after which a steady-state temperature distribution becomes dominant. For brick, the entropy generation contributes only to 12.01% of total entropy generation during the first 100 minutes of charging time. Here the effect of the relatively low diffusivity is understandable, since it takes longer time for the brick to reach the steady-state temperature distribution. The discrepancy in the results is due to large divergence in the thermal diffusivity between the two materials, which contribute to the speed of propagation of heat into solid materials.

For 100 minutes of charging time, and due to the differences in thermal diffusivities, the energy stored in the cast iron unit is 13.47 times that of brick and the internal irreversibility in the cast iron unit is 39.20 times that in the brick unit.

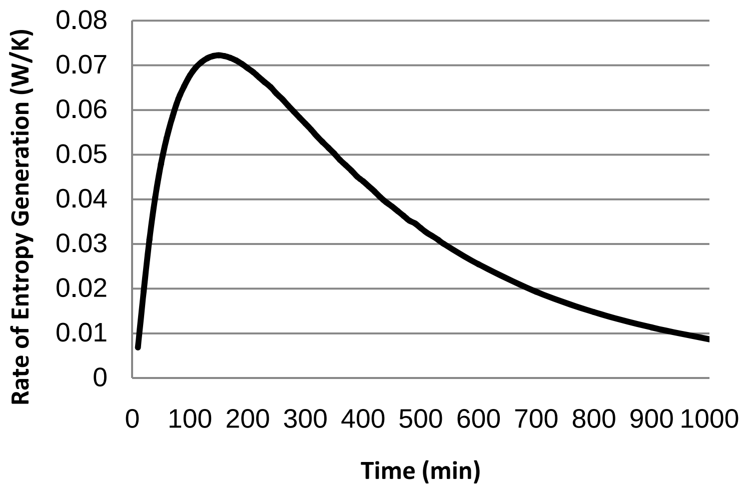

Figure 8: Variation of rate of entropy generation with time for brick

For 1000 minutes of charging time; the steady-state condition is approached, and the effect of the thermal diffusivity is reduced, the stored energy in cast iron unit becomes only 3.375 times of that stored in brick unit. The entropy generation and hence the irreversibility in cast iron storage unit becomes 5.358 times that of brick unit. However, when the same final temperature is attained for both storage units, the storage capacity of cast iron is only 2.5 times the storage capacity of brick, which is the ratio of the heat capacity of the two materials.

Table 3: Summary of the results, entropy generation, irreversibility and stored energy

	For 100 minutes charging time			For 1000 minutes charging time		
	Total Entropy Generation (kJ/K)	Irreversibility (kJ)	Stored Energy (kJ)	Total Entropy Generation (kJ/K)	Irreversibility (kJ)	Stored Energy (kJ)
Cast Iron	10.0835	3006.3956	31432.31	12.282	3661.856	36753.75
Brick	0.2572	76.6803	2332.742	2.1412	683.3988	10890.12

The results indicate that, materials with high thermal diffusivities produce higher internal entropy generation in comparison with materials with lower thermal diffusivities. However as the steady-state condition is approached, the entropy generations for both materials come close to each other.

CONCLUSIONS

A computer program in FORTRAN is developed to simulate numerically the performance of a sensible heat thermal energy storage unit. The following statements may be highlighted:

- Materials with higher thermal diffusivities produce higher entropy generation during the transient period.
- The discrepancy in entropy generation within the materials of different thermal diffusivities is reduced as the steady-state is approached.
- The second law of thermodynamics is an important tool for selecting storage materials and operating thermal energy storage units.
- Storage units could be designed to minimize irreversibility rather than to maximize the amount of energy stored.

NOMENCLATURE

c_p	specific heat, J/kg.K
D	diameter, m
I	irreversibility, J
k	thermal conductivity of the storage material, W/m.K
L	length of the storage unit, m
r	radius, radial coordinate, m
r^*	dimensionless radius
S	entropy J/K
t	time, s, min.
T	temperature, K
u	velocity, m/s
z	axial coordinate

Subscripts

gen	generation
i	inner
o	outer
0	ambient condition

Greek letters

α	thermal diffusivity, m^2/s
θ	dimensionless temperature
ρ	density, kg/m^3

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