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Expanding Heisler chart to characterize heat transfer phenomena in a building envelope integrated with phase change materials

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ABSTRACT

Building envelope integrated with phase change material (PCM) can provide thermal energy storage (TES) distributed in its entire surface area and inhibit the need for enhanced thermal mass in lightweight buildings. Selecting the most appropriate PCM wallboard based on its thickness and thermo-physical properties is the main challenge in the design of net-zero energy buildings and high performance buildings; yet, there is a lack of an appropriate design tool. To develop a design tool, characterizing transient heat transfer phenomena of wallboards impregnated with PCM during charging procedure is required. Accordingly, this study focuses on the characterizing heat transfer of PCM wallboards, and to identify the influential parameters on the charging procedure of a PCM wallboard. The non-dimensionalized analysis was conducted, and the dimensionless numbers influencing the thermal behavior of a PCM wallboard were identified. Moreover, the correlations between the dimensionless parameters and the performance of the PCM wallboard were determined through a comprehensive parametric study. Consequently, a procedure was developed to expand Heisler chart application to study thermal behavior of PCM wallboards.

1. Introduction

Among different sectors of the primary energy users, building sector is one of the main users. According to the Natural Resources Canada [1] more than 30% of the total secondary energy was used by residential and commercial/institutional buildings. This fact implies that the building sector contributes largely in total energy consumption. Particularly, in extremely cold/hot climate areas, space heating/cooling results in high energy consumption. The data from the National Resources Canada [1] also shows that space heating accounts up to 63% of the total energy used in non-industrial buildings. Extracted from this data, electricity is an exclusive source of energy for space conditioning in buildings. The electrical energy demand has a daily variation due to the combination of activities in industrial, commercial, and residential sectors. This results in peak (mostly in early morning) and off-peak periods. In Quebec, Canada, 70% of residential buildings and 60% of the commercial and institutional sector utilize electricity for space conditioning [2]. 80% of the total load of all-electric households during peak hours results from space conditioning. Also, the combined space heating load of the non-industrial buildings accounts for almost 40% of the total electric utility peak during winter peak hours [3]. According to Hydro Quebec [4], during the peak period in winter the electricity cost for the supply side is 10 $/kW and it is increased to 100 $/kW in 2015. Taking this information into account, shifting a significant portion or the entire space conditioning energy consumption to off-peak periods would have significant economic impact on both the supply and demand sides. The shifting of the demand from peak periods to off peak periods can result in a significant reduction of a building's operational costs of the demand side [5]. Meanwhile, the capital investment in the equipment that generates power in peak periods may reduce on the supply side.

The shifting can be accomplished by storing energy during off-peak periods to be utilized during peak ones and other time of a day. Building envelope and building central heating system have been used as thermal energy storage (TES) [6,7]. Moreover, the application of phase change materials (PCMs) as latent heat thermal storage draws interests due to its high energy density. The application of PCM as a TES in buildings was reviewed in details by previous researchers [8–13]. Building envelope impregnated with PCM can provide latent heat TES distributed in the whole building envelope surface area and evade the need for enhanced thermal mass in lightweight buildings. Nevertheless, there is a lack of a general framework to select and size a PCM wallboard, which can be

Abbreviations: TES, thermal energy storage; PCM, phase change material.

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Nomenclature

T	temperature (°C)
$\Delta T = (T_m - T_s)$	melting range (°C)
ρ	density (kg m^{-3})
C	specific heat capacity (J kg^{-1} K^{-1})
t	time (s)
k	conductivity (W m^{-1} K^{-1})
x	space coordinate (m)
L	latent heat (J kg^{-1})
α	thermal diffusivity (m^2 s)
h	heat transfer film coefficient (W m^{-2} K^{-1})
l	wallboard thickness (m)
f	liquid fraction
S_L	slope
A_1	constant
λ_1	constant

Dimensionless parameters

X	dimensionless space coordinate
θ	dimensionless temperature
Ψ	dimensionless temperature constant
Fo	Fourier number
Ste	Stefan number
Bi	Biot number

Subscript

f	fusion
s	solid/solidification
li	liquid
m	melting
fl	fully liquefied
op	operating temperature indicator
pc	PCM
Low Op.Temp.	the lowest operating temperature
High Op.Temp.	the highest operating temperature
ref	reference
i	initial
∞	ambient
in	indoor

employed along with an appropriate control strategy to shift and shave the peak load.

Although there are a number of simulations tools to simulate the thermal performance of a building with PCM wallboard (e.g. TRNSYS, Energy Plus, and ESPR), a simple design tool can help to size the optimum thickness of a required PCM wallboard quickly. Bastani et al. [14] highlighted the requirement of a design tool based on dimensionless parameters and identified the effective dimensionless numbers that influence the performance of a PCM wallboard. To effectively employ the latent heat storage of a PCM wallboard, they defined the design objective as to have a fully charged PCM within given charging time. Thus, Fo_{fl} as the Fourier number calculated for a fully charged PCM wallboard and the effect of Biot number (*Bi*) and Stefan number (*Ste*) on the performance of PCM wallboard was characterized. The outcome was a chart, which can be used to calculate the time that a PCM wallboard has a temperature over than a design value. Therefore, the concept of the chart is similar to Heisler chart [15] for transient heat transfer of conventional building material. In addition to *Bi* and *Ste*, other dimensionless parameters were introduced as the effective parameters in sizing a PCM wallboard. These parameters are resulted from the phase transition nature of a PCM in room air temperature. Characterizing the impact of those parameters on the charging performance of a PCM wallboard results in a framework to select and size a PCM wallboard to be applied in a building envelope. Moreover, illustrating the correlation between those dimensionless parameters creates a number of charts, which can be considered as the expansion of Heisler chart from conventional materials to PCMs.

This study reports the development of a procedure to characterize the transient thermal behavior of PCM wallboards. A non-dimensional approach is used to characterize the impact of effective parameters on the charging performance of a PCM wallboard.

2. Expanding Heisler chart

One concern in building operation is the peak-demand shifting which is beneficial for both supply and demand sides. Installing PCM wallboard in building envelope provides the required medium to store relatively large amount of energy in the form of latent heat during off-peak hours. Consequently, longer shift of energy is achieved and less frequent air conditioner is needed during day. The stored energy is in its highest possible value when PCM is fully charged. A PCM wallboard is called fully charged when its phase state is completely changed from one phase to another (i.e., solid to liquid for heating application, liquid to solid for cooling application). To evaluate the phase status of a wallboard, its temperature profile across its thickness is required. Considering the transient nature of the heat transfer to/from the wallboard, the temperature profile is changing as a function of time and location.

Transient heat conduction analysis in a non-PCM[1] plane wall has been discussed in details in heat transfer textbooks and its non-dimensionalized one-dimension analysis defines temperature within inside a wallboard as a function of three independent variables [15]:

$$\theta = f(X, Bi, Fo) \quad (1)$$

Here, θ is the dimensionless temperature inside a non-PCM wallboard as a function of time and location.

$$\theta(X, Fo) = \frac{T(x,t) - T_\infty}{T_i - T_\infty} \quad (2)$$

The other variables are *Fo* and dimensionless spatial coordinate as follow:

$$\text{Dimensionless spatial coordinate} : X = \frac{x}{l} \quad (3)$$

$$\text{Fourier number} : F_o = \frac{\alpha t}{l^2} \quad (4)$$

where θ is the transient dimensionless temperature profile in a non-PCM wall exposed to convective heat transfer on both surfaces. Therefore, it has a non-zero heat transfer boundary condition (Fourier boundary condition) on its surfaces and a zero heat transfer boundary condition (Neumann boundary condition) in the center due to the symmetrical boundary condition.The approximate analytical solution for θ is as follows:

$$\theta = \frac{T(x,t) - T_\infty}{T_i - T_\infty} = A_1 \exp(-\lambda_1^2 Fo)\cos\left(\frac{\lambda_1 x}{L}\right) \quad (5)$$

and for the center of the wallboard:

$$\theta(0, Fo) = A_1 \exp(-\lambda_1^2 Fo) \quad (6)$$

where the constant A_1 and λ_1 are functions of the *Bi* only and their values are presented in Table 4-2 in Ref. [15] against the *Bi*. Also, the graphical solution is presented in a number of charts which are called Heisler charts. The equations and the relative charts can be

[1] In this manuscript, the conventional building materials are called non-PCM.