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Thermal performance of an innovative curtain-wall-integrated solar heater

Chi-ming Lai [a,*], Shuichi Hokoi [b], C.J. Ho [c]

[a] Department of Civil Engineering, National Cheng-Kung University, Taiwan
[b] Department of Architecture and Architectural Engineering, Kyoto University, Japan
[c] Department of Mechanical Engineering, National Cheng-Kung University, Taiwan

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ABSTRACT

This study combined curtain wall structures, building construction practices, heat transfer mechanisms, and natural circulation loop designs to develop an innovative, wall-integrated solar heater based on the concept of an energy-harvesting facade. The heat transfer performance of this prototype was investigated experimentally. The results indicate that the average Nusselt numbers and flow thermal resistances in the heated and cooled sections increase and decrease, respectively, with an increasing modified Rayleigh number under isothermal boundary conditions for the heat sink. During daily use conditions, the system-wide energy harvest ratio of the test cell is between 0.45 and 0.78 and is not significantly affected by the cooling (feed) water flow rates.

1. Introduction

Environmental control devices and/or designs in buildings that are capable of harvesting solar thermal energy can effectively capture and store this solar energy and provide energy through the use of, for instance, a hot water system [1–3] or a low-power thermoelectric material [4]. Thermal energy storage (TES) is the key component for such solar energy use, and it is one of the most promising and sustainable methods for energy storage in buildings. The TES systems used in buildings can be easily divided into three types: sensible, latent, and thermochemical energy storage (TCES). Because of its numerous advantages, such as its wide range of storage temperatures, high thermal capacity, nontoxicity, low cost, and easy obtainability, water is often used as the storage medium in a solar water heating (SWH) system for domestic solar utilization [5–10]. However, more effective integration of solar collection in SWH systems within the building envelope is always desirable [11,12].

SWH technology is also suitable for renewable energy exploitation to be applied in residential building refurbishment. Golića et al. [13] defined a general model of SWH integration into residential building refurbishment techniques. Rodriguez-Hidalgo et al. investigated the instantaneous performance of solar collectors for domestic hot water use using an experimental solar facility [14]. A cool-down test was conducted in [15] using a single storage tank to determine heat loss characteristics. Dominguez-Munoz et al. [16] proposed the application of reliability analysis methods to design solar thermal systems to consider the true stochastic nature of the problem. Corbin and Zhai [17] proposed a BIPV/T collector and demonstrated its potential for providing increased electrical efficiency of up to 5.3% over a naturally ventilated BIPV roof, reducing the negative effects of integration into the building facade.

In this study, we attempt to combine the curtain wall structures, building construction practices, heat transfer mechanisms, and a natural circulation loop design to develop an innovative, wall-integrated solar heater based on the concept of an "energy-harvesting" facade. The main heat transfer mechanism of this prototype is based on the concept of natural circulation loops (thermosyphons). Natural circulation loops with various configurations and operating conditions have been the subject of numerous studies because of their wide range of technological applications. In a natural circulation loop, the fluid flow, which is driven by thermally induced density gradients, removes heat from the heated section of the loop, and that heat can be transferred to a cooler section at a higher elevation. Such a loop can serve as a low-cost and highly reliable passive heat-transfer device. Comprehensive studies on single-phase natural convection loop performance and the effects of various parameters, such as heated and cooled section orientations, tilt angles, wall thermal conductivity, loop heights, and pipe

* Corresponding author at: 1, University Road, Tainan City 701, Taiwan. Tel.: +886 62757575x63136; fax: +886 62090569.
E-mail addresses: cmlai@mail.ncku.edu.tw, lily.lcm@msa.hinet.net (C.-m. Lai).

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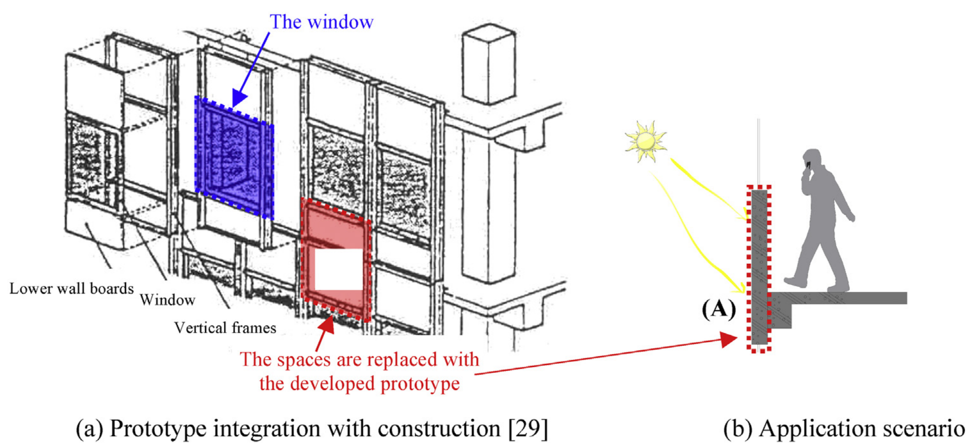

Fig. 1. Prototype development.

diameters, can be found in the literature [18–23]. Improvements in the thermal performance of natural circulation loop systems can be obtained by modifying the loop itself, enhancing the heat transfer properties of either the heated side or cooled side [24–26], or employing various types of working fluids [27]. Joshi et al. [28] reviewed standards based on steady-state models for the outdoor testing of domestic thermosyphon-type solar hot water systems.

In the previous study [29], we developed and experimentally tested an in-wall heat collection prototype that was simplified to a natural circulation loop with a rectangular configuration. The objective of the present study is to provide insights into an innovative, wall-integrated solar heater for which little or no information is available. The thermal performance of the proposed prototype was experimentally investigated for the physical configuration under consideration. Of particular emphasis in this study was the operational performance assessment of the solar heater under practical conditions.

2. Research methods

2.1. Application scenarios and prototype development

The primary considerations during the design stage include how this device would integrate with the building construction and whether this integration would result in an excessive increase in installation costs. After analyzing the construction of conventional exterior walls, we are hopeful that our prototype will be integrated with the "vertical framing and detaching" construction, which is one of the simplest approaches for modularization and has the lowest entry barrier among metal curtain wall systems. The vertical framing and detaching system primarily consists of vertical frames, lintels, windows, and upper and lower wall boards, as shown in Fig. 1(a). Both the location and function of the glazing were maintained. The lower and upper wall boards of the lower curtain wall were integrated and subsequently replaced with the developed prototype.

A prototype was designed based on the heat transfer mechanism, possible construction method, and the application, as shown in Figs. 1(b) and 2(a). In Fig. 2, the insulation materials that fill the gap between the exterior and interior walls have been removed to illustrate the circulation loop components. To assess the thermal performance in our previous study [29], the exterior wall that absorbs solar heat was simplified to a single vertical tube with a constant heat flux boundary as indicated by (1) in Fig. 2(b). During the daytime in summer, the working fluid at the heat source (1) absorbs solar heat, and its temperature increases. Natural convection, driven by thermal buoyancy, causes the hot fluid to flow through the upper horizontal circulation branch (2) and subsequently into the indoor heat sink (3). The fluid dissipates its thermal energy into this heat sink. The fluid cools and flows downward (under the influence of gravity) into the heat source (1) via the lower horizontal circulation branch (4). Using this thermal and flow mechanism, a natural circulation loop develops in the rectangular path. In the loop, the exterior heat source (1) is a vertical branch with constant heat flux heating, and the interior heat sink (3) is a

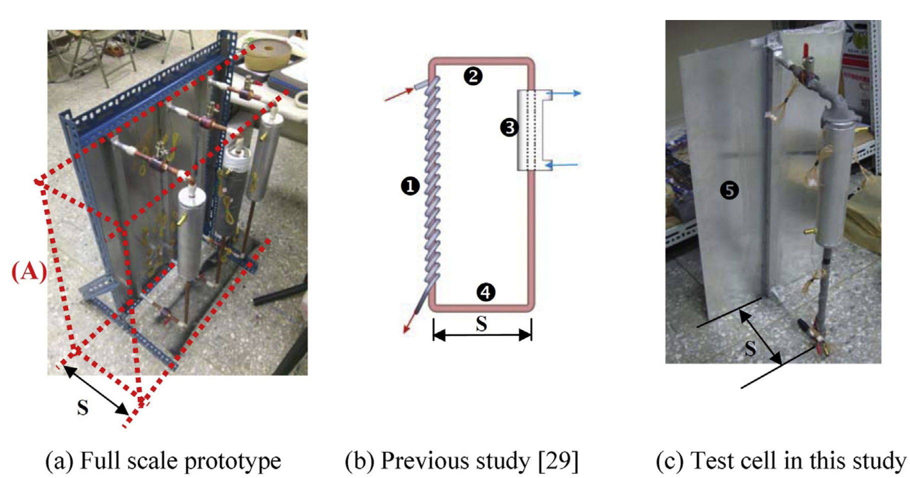

Fig. 2. Solar heater prototype and test cell.