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Numerical prediction of thermal performance of liquid-flow window in different climates with anti-freeze

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ABSTRACT

The application of anti-freeze on liquid-flow window was studied. Its thermal performance was evaluated in the seven climate regions of China. Laboratory tests were first carried out with propylene glycol as the working fluid. The measured results also served for numerical model validation. Then year-round energy performance was predicted for one representing city in each of the seven climate regions. The results show that with strong solar radiation (as in Regions V and VI), the energy saving can be significant in the services hot water system. The yearly electricity savings achieved per unit surface area of the liquid flow window installed are well above 8.3 kWh/m^2, and they are as large as 93.75 and 117.7 kWh/m^2 in Regions V and VI. In the subtropical city Guangzhou however, the use of glycol unfavorably reduces the system thermal efficiency by 13–31% when the glycol concentration is 15–35% with a linear relationship. The impact of liquid concentration is less significant under stronger sunlight. For those regions of cold or extremely cold winter plus warm summer (i.e. in Regions I, II, VI and VII), the replacement of anti-freeze with water in the summer months can be a good practice to maximize the thermal performance.

1. Introduction

Liquid flow window (LFW) is an active and passive solar thermal device that makes use of the glazed building façade to heat up water [1]. The type shown in Fig. 1 is a multi-glazing system with a flowing liquid layer in the window cavity. Through the connection to a double-pipe heat exchanger at the top of the window frame, the liquid flows in a closed loop under the thermo-syphon effect, like what happens in a thermosyphon solar collector. The energy flow paths at this LFW is indicated in Fig. 1 (b); the corresponding heat balance equations can be found in our pervious publication [2]. A major part of infrared radiation absorbed at the glazing is extracted by the flowing liquid in cavity. So the direct solar heat transmission is weakened whereas the visible light transmission is not affected. In hot summer both the air-conditioning load and the window surface temperature are reduced. As a result, the indoor thermal environment is improved. The extracted infrared is released to the cold feed water at the heat exchanger for subsequent services hot water production. LFW is therefore a novel cost effective technology in sustainable building development. It was found that in sub-tropical Hong Kong with the use of absorptive glass panes in double-glazed LFW, the annual reduction in room cooling energy can reach 32% as comparing to the traditional air-sealed double glazing, and 52% as comparing to single glazing systems [2]. In a similar study of Gil-Lopez and Gimenez-Molina in Spain [3,4], 18.26% annual saving in space heating-and-cooling energy was achieved by using a double-glazed LFW with laminated glass panels. In their proposed water circuit, a group of LFWs were connected in parallel and to a remote plate-type heat exchanger through pump circulation; the system design is slightly different form our case here presented.

Other LFW system designs are also possible. In the study of Gonzalo and Ramos [5], pump circulation was also adopted but the other side of the heat exchanger was a shallow geothermal system in which the solar heat was finally transmitted to soil. The supply water temperature to LFW was purposefully controlled to 25 °C in summer and 21 °C in winter. They showed that for a non-air-conditioned room in Spain, the room temperature with such a LFW system could be reduced by 17 °C in summer as compared to the case with traditional double glazing. In winter, the cold spots on the window surface were eliminated. And thermally comfortable

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Nomenclature

A	heat transfer area, m^2
c	specific heat capacity, J/(kg·K)
D	thickness
m	hydraulic diameter of window cavity, m
f	linear friction loss factor
g	gravity constant, m/s^2
G	solar intensity, W/m^2
h	heat transfer coefficient, $W/(m^2 \cdot K)$
m	height of flow path
k	thermal conductivity, W/(m·K)
L	length of flow path, m
M	mass flow rate, kg/s
Nu	Nusselt number,
P_f	friction loss, N
P_T	thermosiphon driven force, N
P_r	Prandtl number,
R_e	Reynolds number,
T	Temperature, ∘C
t	time, s
u	water flow velocity, m/s
v	wind speed, m/s
y	height of window, m

Subscripts

1,2,3,4	surface numbers
a	ambient
C	convective
cout	cold fluid outlet
hin	hot fluid inlet
in	inner glazing, inlet
max	maximum
min	minimum
Out	outer glazing, outlet
r	radiative, room
w	water
up	upward flow
down	downward flow

Greek

α	solar absorption coefficient
ρ	density, kg/m^3
ε	emissivity, -; heat exchanger effectiveness,
Θ	absolute temperature, K
σ	Stefan-Boltzmann constant, 5.67×10^{-8} $W/(m^2 \cdot K^4)$
ζ	local friction loss factor,
ν	kinematic viscosity, m^2/s
μ	kinetic viscosity, Pa·s

room environment could be achieved year round. On the other hand, the energy saving potential of the buoyant-flow LFW system (Fig. 1) was also evaluated [6] under the warm climate of Hong Kong. Based on a case study of sports center application, a triple-glazed system (with clear glass + insulation glass unit combination) was adopted [7,8]. The thermal (water heat gain) efficiency was found in the range of 20%–36.6%, and the reductions in annual cooling loads were from 22% to 35%, depending on the daily weather conditions. Better energy saving performance was achieved by using phase change material at the heat exchanger for thermal storage [9].

While good energy saving potential was found in the above case studies in the warm climate regions, so far no comparative study was conducted to evaluate the energy performance of LFW under a full range of climate conditions. It is a well-known fact that in cold winter, water-freezing and ice formation may damage the system equipment and pipework.

Various freeze prevention technologies are in use for solar energy applications [10–13]. For example, transparent insulation material (TIM) is commonly used in flat-plate solar collectors [14]. But the drawbacks are the considerable reduction in visual light transmission, as well as the required extra thickness and weight. Enhanced thermal insulation [15] is another popular anti-freeze method. One example closely related to LFW application is the inclusion of a thermally insulated glazing system between two liquid chambers – as proposed in the "fluidized glass façade" system of a recent European Commission project [16–18]. With the outer liquid chamber evacuated in winter, solar energy can be transmitted into the room space directly through the inner glazing. On the other hand, warm water at a controlled temperature can be circulating in the inner liquid chamber [16] so that the glazing itself can be used as a room heating device to maintain a comfortable indoor environment. As a matter of fact, auxiliary heating is an "active" (because of the power demand) but effective means in water freezing prevention [19,20]. Alternatively, the use of anti-freeze additive like glycol is a popular "passive" measure that purposely lowers the ice point of the working fluid [21,22].

Two types of glycols are often used as additive in freeze prevention [23]. They are: (i) the ethylene glycol (EG) that has better thermo-physical properties, and (ii) the propylene glycol (PG) which is less toxic. Norton et al. [24] studied the impact of PG concentrations on the freeze protection effect. It was concluded that 25% PG could be desirable for the city of London (with temperate oceanic climate), and a higher ratio was needed for places with winter temperature below −10 °C. These were at the expense of drop in thermal conductivity [25,26] and thermal efficiency [27].

As far as LFW is concerned, the use of TIM structure is undesirable because of the natural light blockage, and so is auxiliary heating in view of the extra power demand. Glycol solution is then the most effective and practical passive means. Comparing with EG, PG is considered safer for window application.

In this study, laboratory test was first conducted on a glycol-filled LFW prototype. The experimental results served the dual purposes of thermal performance analysis and numerical model validation. In China, there are seven climate regions from Regions I to VII as listed in Table 1, together with the climate characteristics and a representing city of each. Accordingly, the energy performance of the same LFW was evaluated at each of the seven named cities through numerical analysis. The appropriate PG concentration was used in each case, with the effect of PG concentration on the LFW energy performance first evaluated. To carry out such year-round performance evaluation with either water or anti-freezer as the working fluid, a city with no freezing risk had to be chosen. Thus Guangzhou in Region IV was selected as the illustrating example.

The exploitation of the energy saving potential of LFW in different climate regions is meaningful for examining its application potential. This will finally help in the reduction in primary energy consumptions and in the worldwide carbon emission.

2. Laboratory tests

The laboratory works were conducted in Changzhou (at 31.8 °N