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Effectiveness of distributor design on buoyant-water-flow window performance

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Abstract

Water flow window is a multi-glazing system with a flowing water layer in the window cavity. In its buoyant-flow design, the water flows in a closed loop between the window cavity and a double-pipe heat exchanger above the glass panes. Thermal energy carried away by the warm water stream in the cavity was released to the cold feed water in the heat exchanger for supporting the domestic hot water system. In the original conceptual design, two headers with evenly distributed openings are located at the top and bottom ends of the window cavity to provide flow uniformity. In the new design, these two headers were removed. The system performance was evaluated via both experimental measurement and computer simulation. The findings indicate that the circulating water flow is improved. The surface temperature of the inner glass pane can be more uniform than the original design. The overall system thermal performance is generally not affected. Advantages lie in the reduction in the material use and overall weight of the window and in the manufacturing, delivery and site handling costs.

Keywords – window solar-heat absorption; fluid-flow window; integrative active and passive system design; building energy conservation (key words)

1. Introduction

Water-flow window is a multi-glazing system with a flowing water layer in the window cavity [1]. In its buoyant-flow double-glazing design as in Fig. 1(a), the water flows in a closed loop between the sealed cavity of the two glass panes and a double-pipe heat exchanger at the top via interconnecting tubing. Under sunlight, the absorbed solar thermal energy is carried away by the warm water stream in the cavity and is then released to the cold feed water in the counter-flow heat exchanger. This can be subsequently used for supporting the domestic hot water system as a pre-heating device. Because of the thermal extraction, the room cooling load is reduced. Thus both the energy consumptions of the domestic hot water and the room air-conditioning systems are reduced. Besides, the natural daylighting penetration is hardly affected in the presence of the thin water layer. This is particularly beneficial for cooling-dominated climate such as for hotels or sports center applications. Thermal performance of the system had been evaluated under various design conditions with both experimental measurements and validated numerical modelling and simulation methods [2-3].

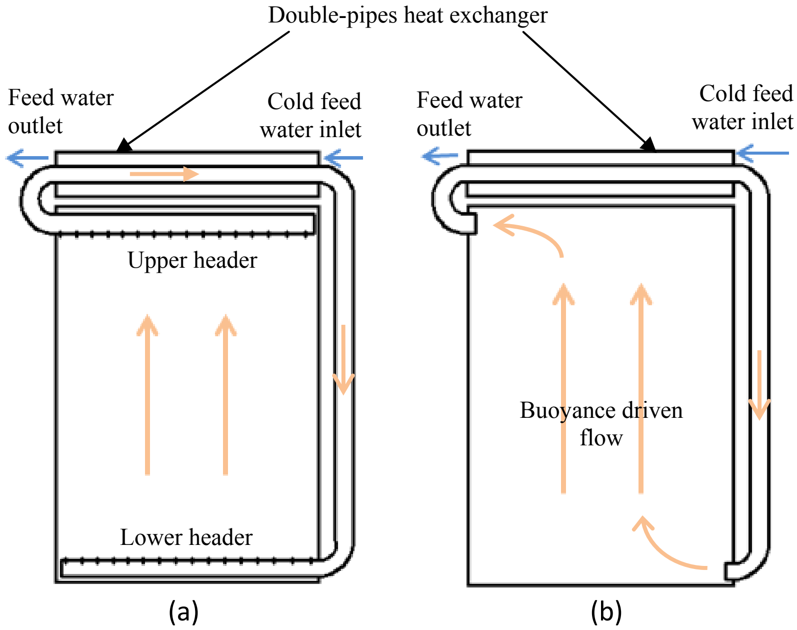


Fig. 1. Buoyance driven flow circuit in water-flow window systems: (a) with distribution headers; (b) without headers

In the original conceptual design, two headers with evenly distributed openings are located at the top and bottom ends of the window cavity, as in Fig. 1(a). This is intended for ensuring flow uniformity across the window width during the solar heat absorption process. In the new design, these two headers were removed, as illustrated in Fig. 1(b). The purpose is to reduce the overall friction loss of water flow in the circulation loop. The system energy performance of the new design was first evaluated through experimental measurements, and then completed by numerical analysis.

2. Research Methodology

With the construction of an experimental prototype with modified design, laboratory tests were conducted for a whole week in late October (from 21st to 27th). The window was installed at a south-facing vertical wall of an air-conditioned laboratory chamber located at the flat roof of a multi-story university building. The overall dimensions of the chamber were 3m (L) × 3m (W) × 3m (H). The global solar radiation on horizontal and vertical surfaces was measured by pyranometers mounted next to the prototype at test. The cold feed water flow rate was found using measuring cup and stop watch. Operating temperatures were measured with type-T thermocouples. Glazing surface temperatures at three different vertical positions were recorded, as labelled in Fig. 2. Temperatures at inlets and outlets of hot and cold water streams, indoor and outdoor air temperatures were also collected. The cold water flow rate was sampling checked at 30-minute interval to ensure stability from the supply source, and the remaining data were recorded by data-logger at 2-minute interval during daytime.

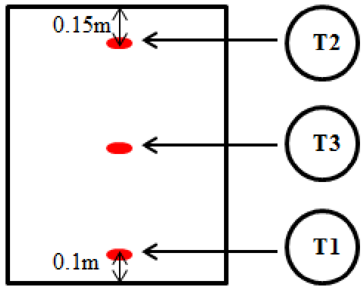


Fig. 2. Positions of temperature measuring points at exposed glass surfaces

In the numerical analysis, the original validated simulation program, which was self-developed based on the finite difference energy and flow balance approach [3] (for buoyant flow window system with distribution headers), was modified to match the present case with revised flow resistances. See the flow chart in Fig. 3. Heat transfer at the heat exchanger was determined the same as before using the NTU-ε method [4]. Experimental validation and calibration tests were successfully completed using the laboratory data. Here the global horizontal solar radiation, air temperatures, inlet temperature and flow rate of the cold feed water stream were used as the simulation inputs. The simulation results of glazing surface temperatures, hot water inlet (incoming) and cold water outlet (leaving) temperatures at the heat exchanger were compared to the laboratory data to ascertain the quality of the computer program in use. Then finally, the overall system thermal performance was evaluated based on additional simulation runs and numerical analysis making use of the typical weather data set [5].

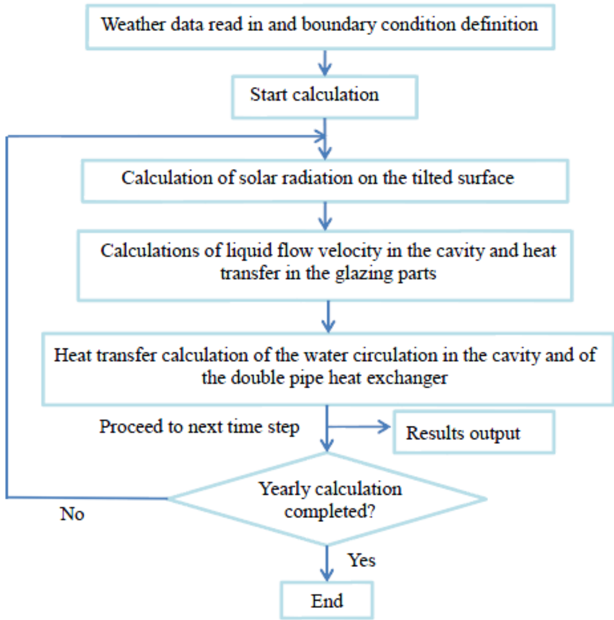


Fig. 3. Flow chart of FORTRAN calculation

3. Results and Discussion

3.1 Experimental results

Listed in Table 1 are the daily solar radiation levels, which are the accumulated sum of the measured solar radiation from 8 am to 5 pm on each day.

Table 1. Measured global solar radiation during the test period

Daily radiation level (kWh/m^2)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
	4.188	3.443	3.644	1.903	1.563	2.760	3.378

The variation of inner and outer glazing temperatures are given in Fig. 4 for illustration. It can be observed from the outer glazing case that the temperature levels at the center point (T3) were closer to those at the upper point (T1). This is because of the direct exposure of this glazing surface to incident solar radiation, and the same had been observed in the previous case with distribution headers. For the inner glazing, T3 was also closer T1. This was different from the results in the previous design case. The improved uniformity in surface temperature is deemed to be the reason, as a result of higher flow circulation when the friction loss has been reduced [4].

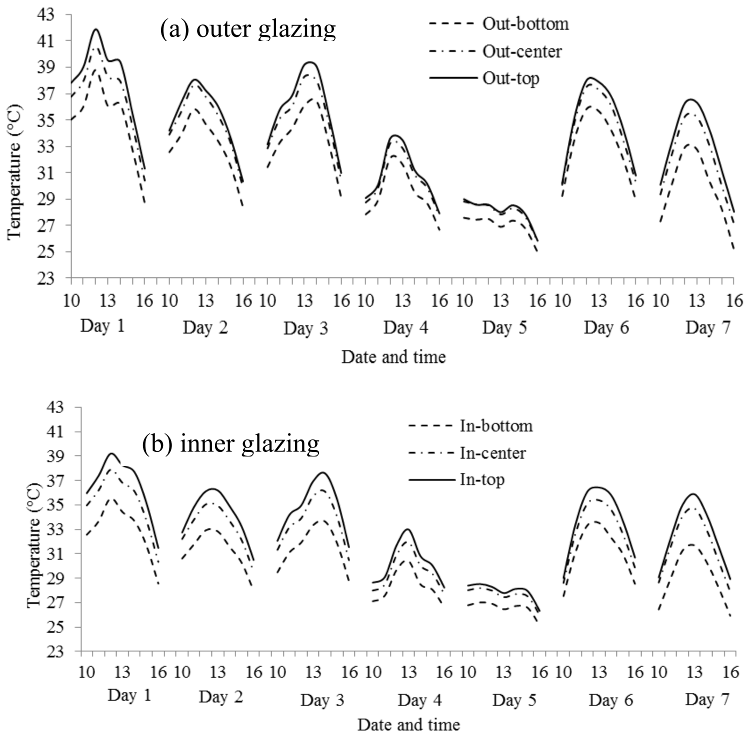
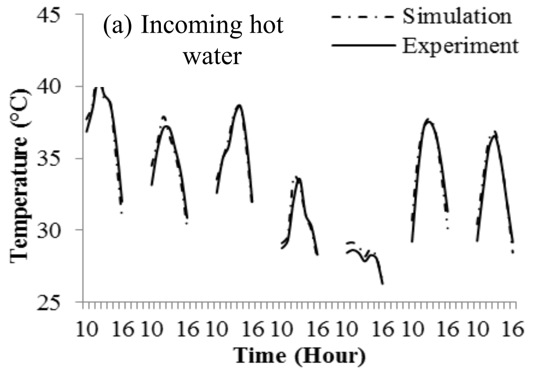


Fig. 4. Variation of glazing temperature at three different vertical positions for: (a) outer glazing; (b) inner glazing

3.2 Program validation

Fig. 5 shows the comparison of simulation outputs with measured data for hot water inlet and cold water outlet temperatures during the test period. Good agreement between the two can be seen. Accurate prediction of these two temperatures is important for the accuracy in thermal performance evaluation. Similar good accuracy was also found in glazing temperature predictions. This verified simulation program was then applied in further system evaluation with the use of the Typical Meteorological Year (TMY) weather data of Hong Kong.



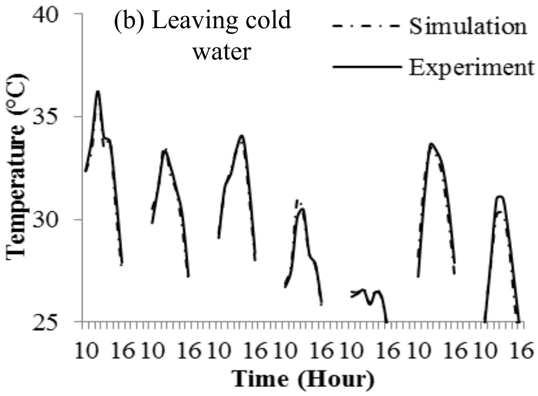


Fig. 5. Comparisons of computer simulation and experimental results at heat exchanger: (a) inlet temperature of hot water; (b) outlet temperature of cold feed water,

3.3 Numerical evaluation: cases with and without headers

System performance was evaluated by means of: (i) mass flow rate of water in circulation, (ii) useful feed water heat gain (corresponding to reduction in DHW system energy consumption), and (iii) room heat gain (corresponding to reduction in air-conditioning energy consumption). Table 2 lists the basic parameters of the two window systems in this study.

The results show that the water circulation can be improved by eliminating the distribution headers. The comparisons were made reference to typical summer and winter weeks as shown in Fig. 6 (a) and (b) respectively. By eliminating the headers, the water circulation is found increased by 17% on average during the typical summer week (2^{nd}-8^{th}

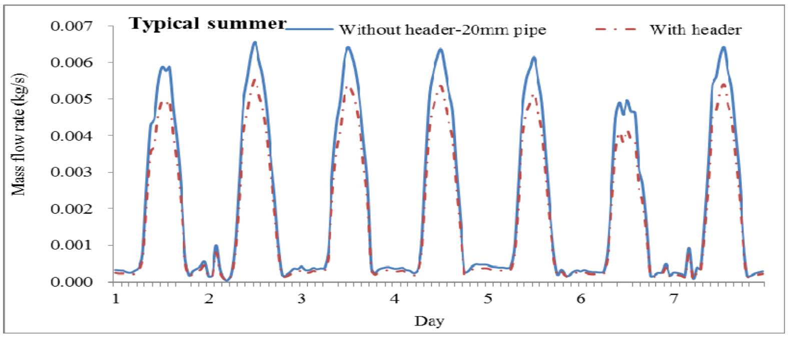
September), and 20% on average during the typical winter week (8^{th}-14^{th} January).

Table 2. Basic parameters of the two glazing systems for performance evaluation

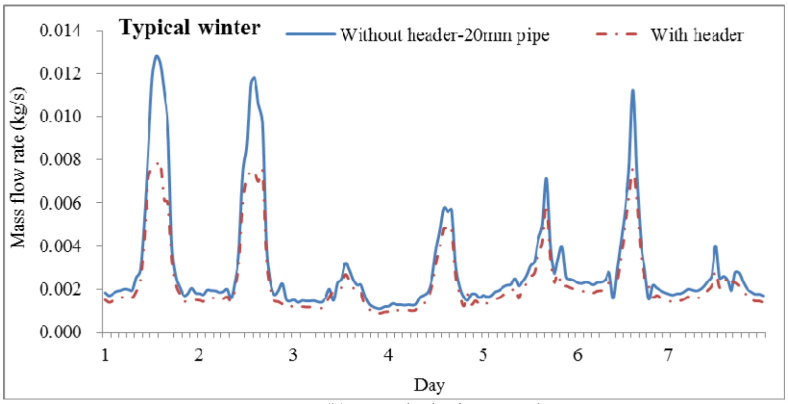
Parameters	For both Case 1 and Case 2
Glass panes (outer and inner):	
Material	Absorptive glazing
Dimensions (height × diameter × thickness)	1.2m×0.8m×0.012m
Density	2515 kg/m^3
Specific heat	810 J/kg.K
Optional properties:	
Reflectance (front / back)	0.048 / 0.048
Transmittance	0.307
Absorptivity	0.645
Double-pipe heat exchanger:	
Dimensions (length × diameter × thickness)	2.0m×0.03m×0.001 (outer pipe) 2.0m×0.02m×0.001 (inner pipe)
Material	Copper
Thermal conductivity	401 W/m.K
Density	7900 kg/m^3
Circulating tube:	
Material	Stainless steel
Diameter	0.02m
	For Case 1 only
Distribution headers:	
Dimensions (height × width × thickness)	0.027m×0.014m×0.001m
Opening diameter	0.002m
Interval spacing	0.03m

The year round thermal performance was shown in Table 3, with the monthly data listed. It can be seen that despite the improvement in water circulation rate, there are only slight improvement in useful water heat gain, and basically no change to room heat transmission year round. This is owing to the self-regulating characteristics of the heat transfer processes in the buoyant-flow window design. The yearly water heat gain of Case 2 was larger than that of Case 1 by about 4%. For both cases, the water flow inside the window cavity remains laminar by nature, and so is slow and highly stable. The almost unchanged thermal transmission of the two cases was caused by the very similar water and glazing surface temperatures. As illustration, Fig. 7 (a) and (b) show respectively for the typical summer and winter weeks, the simulation results of the water temperature at the outlet of the window cavity (HOUT) and the corresponding temperature rise of water (HDT) in the cavity. It can be observed that in both graphs, the water temperature at the outlet of the cavity (HOUT) were more or less of the same value for Case 1 (with headers) and Case 2 (without headers).

However, the water temperature rise HDT of Case 1 is generally greater than Case 2 for both summer and winter periods. This compensates for the change in water flow rate in the opposite direction. A thermal efficiency of 12% in water heat gain is generally achievable for both Case 1 and Case 2.



(a) Typical summer week



(b) Typical winter week

Fig. 6. Comparison of water circulation flow rates for cases with and without headers during typical summer and winter weeks

Based on the above findings, the main advantage of removing the distribution headers is therefore not in achieving better system energy performance, but in overall material and weight reduction, and as expected, leading to lowered manufacturing, delivery and site installation costs.

Table 3. Comparison of system thermal performance between Case 1 (with headers) and Case 2 (without headers)

Months	Water heat gains (kWh)		Thermal transmission (kWh)	
	Case 1	Case 2	Case 1	Case 2
January	16.20	16.80	3.51	3.51
February	11.11	11.73	2.45	2.45
March	32.18	32.20	7.16	7.16
April	22.71	22.71	17.56	17.56
May	26.98	26.98	15.11	15.11
June	21.29	21.29	21.95	21.95
July	27.23	27.23	28.47	28.47
August	30.27	30.27	26.37	26.37
September	29.41	29.41	21.74	21.74
October	45.61	45.61	20.13	20.13
November	54.22	54.22	8.90	8.90
December	60.80	60.80	8.33	8.33
Year round	378.02	379.26	181.68	181.68

4. Conclusion

By eliminating the distribution headers of the buoyant-water-flow window, the water circulation can be improved. This is because of the reduced friction loss at the circulation loop. The water flow inside the window cavity remains laminar. On the other hand, there can be improvement in temperature distribution at the inner glass pane surface. The thermal performance from the aspects of useful water heat gain and room thermal transmission is basically not affected. This demonstrates the self-regulation characteristics of the buoyant-flow heat transfer process. The main advantage of removing the distribution headers lies in the lowered manufacturing, delivery and site installation costs.

Acknowledgment

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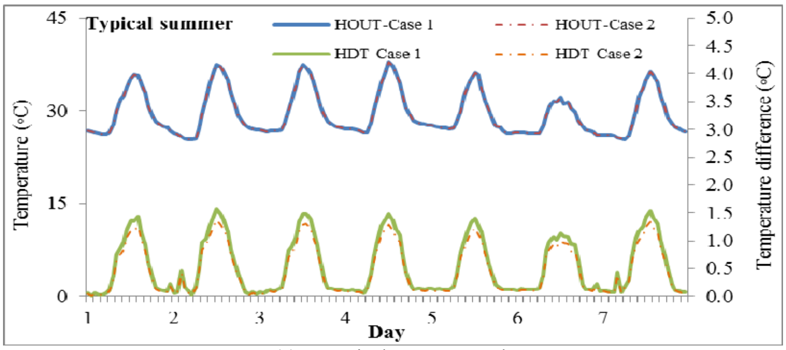
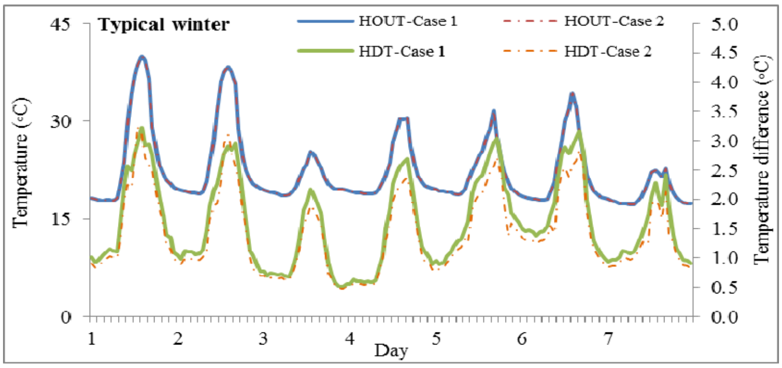


(a) Typical summer week



(b) Typical winter week

Fig. 7. Comparison of leaving water temperature (HOUT) and the water temperature rise (HDT) in the window cavity during typical summer and winter weeks

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