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Performance Evaluation of Innovative Solar-absorbing Façade Panel

Tin-Tai CHOW, Wenjie LIU

***Abstract* — A new solar-absorbing façade panel has been developed in this government-funded project to cope with the urgent needs on building sustainability research, in particular the renewable energy applications. In this paper, two related inventions, namely the water-filled glazing with submerged heat exchanger and the heat-pipe-ring embedded curtain walling, are described. With the use of validated self-developed simulation programs, the energy performance of the glazed and opaque areas of the panel are assessed separately. Performance comparisons were made with the conventional curtain walling. The findings support that with an appropriate coverage of the new façade panel on the building envelope, as well as the appropriate area ratio of the glazed to opaque surfaces, this innovative façade is able to reduce significantly the solar transmission and to generate adequate hot water with promising thermal efficiency.**

***Keywords*—solar-absorbing panel, water-filled glazing, heat pipe technology, building energy conservation, curtain wall**

I. Introduction

Energy use in buildings accounts for 31% of the total energy consumed globally [1]. In modern cities, this often leads to major environmental problems, like air pollution and urban heat island effect [2]. Many countries has strategic plans on green building development, in which the building envelope holds a highly important role. Funded by the Shenzhen municipal government of China, this 3-year research project was launched in 2016, targeting at introducing an innovative solar-absorbing façade for use in modern buildings.

In southern China, including Hong Kong, glazed curtain wall building with aluminum cladding is most popular for modern architecture. Curtain walls are typically comprise a lightweight metallic frame onto which glazed and/or opaque panels are fixed. To bring in the concept of solar absorption as an integrated active and passive technology, it is deemed both the transparent and opaque surfaces can be fully made use of as façade-integrated solar collectors. In this way, the solar collecting area is maximized naturally and no extra space (like flat-roof space) has to be sought.

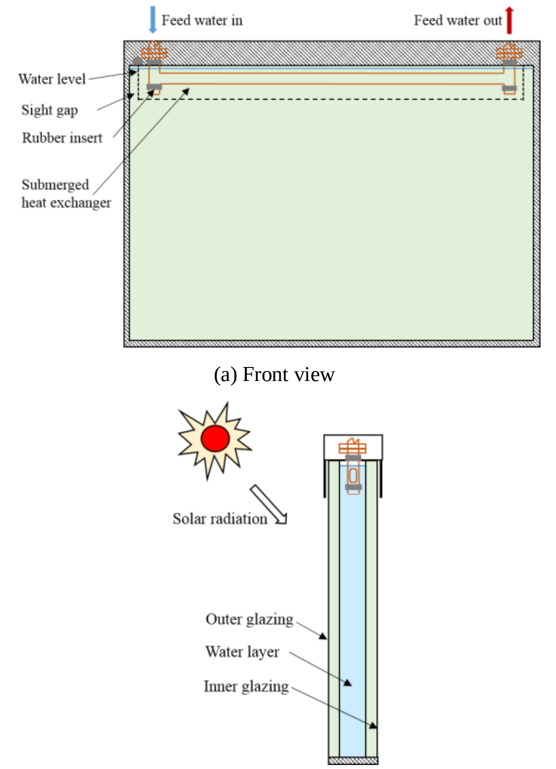
Tin-Tai CHOW
Shenzhen Research Institute, City University of Hong Kong
China

Wenjie LIU
Shenzhen Research Institute, City University of Hong Kong
China

A high-efficiency and large-area solar collection at the external facade is able to reduce effectively the heat transmission as the air-conditioning load, and also to mitigate the back flow of heat to the outdoor space as a source of urban heat island effect. Along this direction, our recommendation is then a factory-assembled aluminum panel for curtain-wall building applications. The novelty lies in the combined use of new water-flow glazing and heat-pipe infill panels as the solar-absorbing devices.

A. Water flow glazing with submerged heat exchanger

Water-flow glazing involves a stream of purified water flowing in the cavity of the double-glazing. The drive can be either buoyant (thermal syphon) or mechanical (pump circulation) type for transporting this enclosed primary water stream to an external heat exchanger and then for passing over the absorbed heat to a secondary water stream. In our innovative design however, the primary water always remains in the cavity like a warm water bath, as illustrated in Fig. 1.



(a) Front view

(b) Side view

Figure 1. Water-filled double-glazing with submerged heat exchanger

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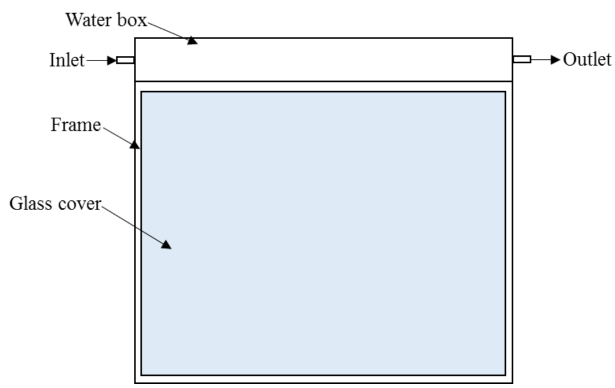
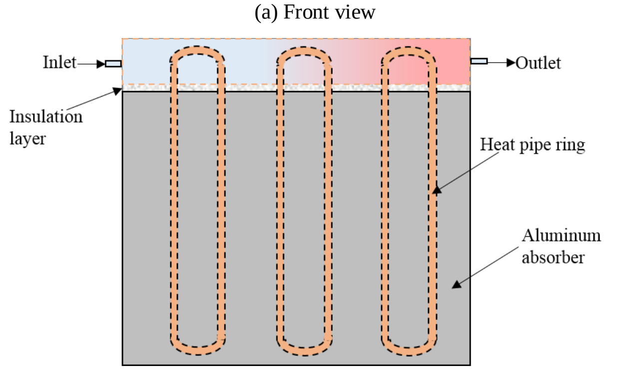
Instead, the secondary water tubing is led into the glazing cavity together with a miniature heat exchanger. This heat exchanger is set horizontally at the top end and is fully submerged underneath the liquid bath level. Comparing with the previous buoyant-flow design [3–5], this new design is more compact by eliminating the external double-pipe heat exchanger. Accompanying the higher thermal efficiency are the savings in material use and the construction cost.

B. *Aluminum cladding with embedded heat-pipe-ring*

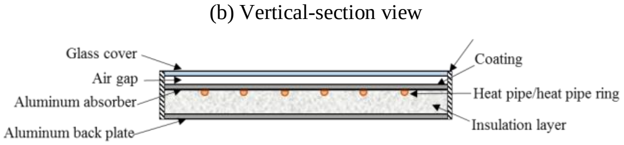
For the opaque façade panel, the innovative heat-pipe-ring is proposed for use in the aluminum curtain walling, as shown in Fig. 2.



(a) Front view



(b) Vertical-section view



(c) Horizontal-section view

Figure 2. Heat-pipe emebedded curtain walling

The heat-pipe array has the evaporator ends attached onto the back surface of an aluminum plate, which is then the thermal absorber with its front surface coated with selective coating. Its condenser ends are inserted into a secondary water flow chamber above the absorber plate. The glass cover at the front retains the penetrated short-wave radiation after its long-wave conversion. The absorbed solar heat is effectively transferred to the cold feed water. The innovative heat-pipe-ring option, instead of the conventional straight heat-pipe design, allows the use of a smaller water-flow chamber and hence increases the thermal absorber surface area.

With the above-mentioned inventions, tailor-made prototypes of the solar-absorbing façade panel, as shown in Fig. 3, were fabricated and tested. Numerical models were also developed and the self-developed computer simulation programs were validated by the laboratory measured data. Then through further numerical analysis, the year-round energy performance of the proposed solar-absorbing panel was fully evaluated.

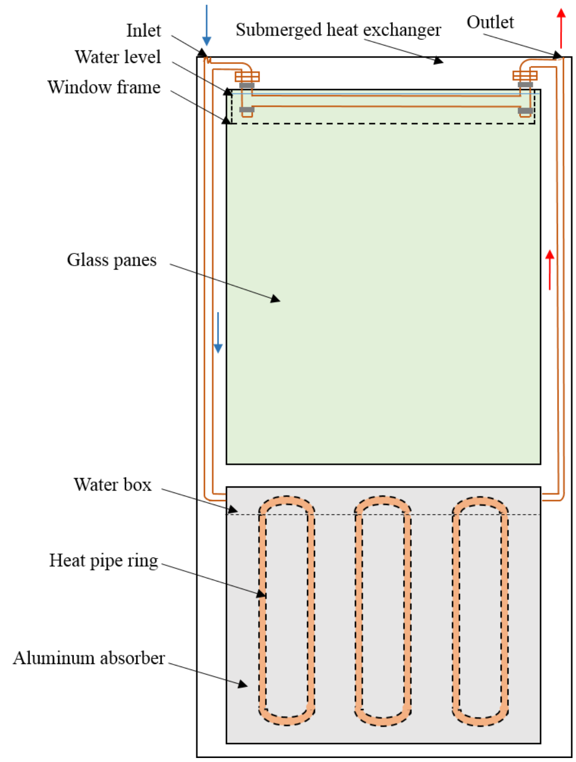


Figure 3. Proposed solar-absorbing façade panel

II. Numerical evaluation of energy performance

The energy performances of the glazed and opaque areas of the façade panel were assessed in terms of water heat gain Q_{water}, water heat gain efficiency η, room heat gain/loss $Q_{room-cooling}$ and $Q_{room-heating}$, and net electricity saving E_{net}. The dynamic thermal performance of each of the two unique areas was analyzed using the typical meteorological year (TMY) weather data of Hong Kong, a well-known subtropical Asian city. The vertical solar façade was assumed facing southwest, which is the orientation in Hong Kong receiving the highest solar radiation throughout a year. In our assessment, the air-conditioned space was assumed occupying 24 hours per day for year-round activities. The indoor temperature was set 25^{o}C for summer from April to October, and 21^{o}C for winter time from November to March.

The design flow rates of the cold feed (secondary) water were at 1300 ml/min and 5000 ml/min for the glazed and opaque panel areas respectively. The water temperature at the inlet was taken the same as the ambient temperature at any simulation time-step (on hourly basis), but not to exceed the range of 5 to 25^{o}C as the extremes, considering adequate pipeline insulation under normal circumstances.

A. Energy performance of the glazed area

For the glazed area, the net electricity saving in this case was determined as the sum of the electricity saving from the hot water system (with 99% electric-heating efficiency) and from the space air-conditioning system (with COP values of 3.5 for room cooling and 4.5 for room heating). The performance of this innovative glazing was compared to the conventional single-absorptive glazing, which is the basic provision for commercial curtain-wall buildings in the subtropical climate. The dimensions and properties of materials used in the water-filled double glazing and the single-absorptive glazing are listed in Table I.

The monthly thermal performances of the two glazing types are displayed in Table II. The results show that the yearly-averaged water heat gain efficiency of the water-filled double glazing reached 30.8%, with the yearly water heat gain at 943.0 MJ per m^2 of the glazing area. The highest monthly-averaged efficiency of water heat gain (at 38.7%) occurred in January, which is favorably the month strong in solar radiation but low in ambient temperature.

Also shown in Table II are the monthly space cooling and heating loads of the water-filled double glazing as compared to the single-absorptive glazing. Because of the short thermal time constant of the glazing constituents and the assumed 24-hour system operation, the above came from simple projection of the room heat gain and loss.

The yearly cooling load of the single-absorptive glazing was found 1617.1 MJ per m^2, and it was only 1004.1 MJ per m^2 for the water-filled double glazing. This means that the newly proposed solar-absorbing glazing is able to reduce the cooling load of the air-conditioning system by 37.9%.

On the other hand, the innovative glazing system leads to 4.2% reduction in space heating load. Taking into account the heating and cooling COPs of the air-conditioning system, the water-filled double glazing is able to achieve 33.2% of the annual saving in air-conditioning electricity consumption. And the electricity saving was about 1130.8 MJ per m^2 annually, in terms of both the air-conditioning system and the hot-water services system.

TABLE I. PARAMETERS OF WATER-FILLED DOUBLE GLAZING WITH SUBMERGED HEAT EXCHANGER AND THE SINGLE-ABSORPTIVE GLAZING

parameters		values
Glass pane		
1.	Length × width × thickness (m)	1.3 × 1.0 × 0.008
2.	Solar transmittance at normal incident	0.421
3.	Solar absorbance at normal incident	0.527
4.	Emissivity	0.84
Heat-transfer liquid tubing (copper tubing)		
1.	Length (m)	1.3
2.	Cross-section (m)	0.006 × 0.006
3.	Tubing wall thickness (m)	0.001

TABLE II. THERMAL PERFORMANCE ASSESSMENT OF THE WATER-FILLED DOUBLE GLAIZNG WITH SUBMERGED HEAT EXCHANGER AND THE SINGLE-ABSORPTIVE GLAIZNG (UNITS IN MJ/M^2)

Months		Water-filled double glazing				Single-abs-glazing		Comparison
	G_{tt}	Q_{water}	h	$Q_{room-cooling}$	$Q_{room-heating}$	$Q_{room-cooling}$	$Q_{room-heating}$	E_{net}
Jan.	297.1	114.9	38.7%	62.3	80.9	134.6	78.2	136.1
Feb.	241.4	90.1	37.3%	44.5	73.6	99.4	76.2	107.2
Mar.	218.3	73.5	33.7%	43.0	49.8	84.4	54.2	87.0
Apr.	197.6	50.3	25.5%	55.3	19.3	82.4	24.8	59.8
May.	192.6	51.3	26.6%	80.5	1.4	103.4	2.0	58.5
Jun.	186.0	59.3	31.9%	92.5	0.1	115.1	0.2	66.3
Jul.	243.0	80.1	32.9%	118.2	0.0	158.0	0.0	92.2
Aug.	258.4	79.2	30.6%	120.4	0.0	170.2	0.0	94.2
Sept.	249.5	67.7	27.1%	108.6	0.0	160.0	0.0	83.1
Oct.	321.7	73.1	22.7%	113.9	3.0	183.3	4.1	93.9
Nov.	305.1	80.2	26.3%	83.2	24.7	153.8	27.4	101.8
Dec.	354.4	123.4	34.8%	81.8	66.9	172.6	66.8	150.6
Yearly	3064.9	943.0	30.8%	1004.1	319.7	1617.1	333.8	1130.8

B. *Energy performance of the opaque area*

The design parameters of the opaque façade panel were listed in Table III. With the secondary water supply to the glazed and opaque areas in parallel connection, the feed water temperature condition was always the same both areas in this performance evaluation.

The thermal performance of the opaque panel area across the months, including the water heat gain and the water heat gain efficiency, are compared with the conventional aluminum veneer curtain wall (AVCW). The results are shown in Table IV, with the incoming global solar radiation also shown for ready reference. It can be observed that the monthly water heat gain and the monthly total solar irradiation on the vertical façade shared the similar trend. This implies that the solar irradiation intensity is one key influencing factor of the water heat absorption. The month having the highest accumulated global solar irradiation on the vertical façade surface is most often having the highest monthly water heat gain. Hong Kong has the highest monthly global vertical solar irradiance of 339.5 MJ per m^2 in December, as well as the highest monthly water heat gain of 249.9 MJ per m^2. The highest monthly-averaged efficiency of 75.7% occurred in August. Over the year, the water heat gain was 2227.0 MJ per m^2 annually, and the year-average water heat gain efficiency reached 73.7% for this opaque area. This is 2.4 times of that of the glazed area.

The results of the monthly room heat gain and monthly room heat loss of this opaque panel area and the referenced AVCW are also given in Table IV for ready comparison. It can be seen that in the presence of the insulation layer in the middle of the opaque panels, the room heat gain and room heat loss were negligibly small comparing with those of the glazed area. Under the subtropical climate conditions of Hong Kong, the annual room heat gain of the solar-absorbing opaque panel at 38.8 MJ/m^2, which is only 3.9% of that of the water-filled glazing. This is only 1.7% for the annual room heat loss at 5.5 MJ/m^2. Similar situation occurs in the conventional curtain wall with single-absorptive glazing, i.e. at 2.9% and 1.7% for annual room heat gain and room heat loss respectively.

Considering the COPs of the air-conditioning system and the efficiency the water-heating system, the monthly net electricity saving of this heat-pipe-ring curtain walling can be calculated making reference to the AVCW. The yearly net electricity saving is then up to 2251.7 MJ per m^2.

TABLE III. DESIGN PARAMETERS OF THE HEAT-PIPE-RING EMBEDDED CURTAIN WALLING

Parameters		Values
Aluminum absorber (surface treatment: highly selective blackened nickel)		
1.	Length × height × thickness (m)	1.3 × 1.3 × 0.05
2.	Absorptance	0.97
3.	Emittance	0.18
Insulation layer (rubber foam)		
1.	Length × height × thickness (m)	1.3 × 1.3 × 0.05
Heat pipe / heat pipe ring (Cu-Water)		
1.	Number of pipe rings	3
2.	Length of evaporator section L_e (m)	1.1
3.	Length of condenser section L_c (m)	0.2
4.	Outer diameter of evaporator section (m)	0.01
5.	Outer diameter of condenser section (m)	0.02
6.	Pipe thickness (m)	0.0005
7.	Filling ratio	30%
Water box		
1.	Outer dimensions: length × width × height (m)	1.3 × 0.032 × 0.122
2.	Thickness (m)	0.001

TABLE IV. MONTHLY ROOM HEAT GAINS AND LOSSES OF THE HEAT-PIPE-RING EMBEDDED CURTAIN WALLING (UNITS IN MJ/M2)

Months		Glazed HPR-AVCW				AVCW		Comparison
	G_{tt}	Q_{water}	h	$Q_{room-cooling}$	$Q_{room-heating}$	$Q_{room-cooling}$	$Q_{room-heating}$	E_{net}
Jan.	297.2	220.5	74.2%	2.6	1.6	2.4	1.5	222.7
Feb.	241.5	177.9	73.6%	2.0	1.3	1.6	1.4	179.6
Mar.	218.5	157.1	71.9%	2.5	0.6	2.2	0.6	158.6
Apr.	198.5	143.7	72.4%	1.9	0.6	2.2	0.8	145.3
May	191.2	139.9	73.2%	2.7	0.0	4.2	0.0	141.8
Jun.	183.1	136.4	74.5%	3.0	0.0	4.9	0.0	138.4
Jul.	240.4	179.1	74.5%	3.9	0.0	6.2	0.0	181.5
Aug.	255.7	193.5	75.7%	4.0	0.0	6.0	0.0	196.0
Sep.	247.5	186.7	75.5%	3.8	0.0	4.8	0.0	188.9
Oct.	314.9	231.4	73.5%	4.2	0.1	4.5	0.1	233.9
Nov.	293.3	210.8	71.9%	4.7	0.2	4.4	0.2	212.8
Dec.	339.5	249.9	73.6%	3.4	1.1	3.2	1.0	252.3
Yearly	3021.3	2227.0	73.7%	38.8	5.5	46.6	5.6	2251.7

III. Discussion

Based on the above numerical results, it can be seen that the solar-absorbing façade panel here proposed is highly promising for green building application in the warm climate region. The new water-flow-glazing design can effectively reduce the solar heat transmission which is highly important for a heavily-glazed modern architecture. The heat-pipe-ring incorporation of the opaque panel can act as a high-performance solar hot-water collector, without the need of installing floor-mounted solar collectors using additional supporting frame. The proposed façade system is based on proven technology at low cost. With a 50-50 split of the glazed area to opaque area ratio, the water heat gain efficiency is found to be 52.3% on yearly average basis. Comparing with the conventional curtain walling, the electricity saving could reach 32.8% based on the air-conditioning consumption owing to the reduced solar transmission.

It is deemed that the energy performance of the proposed solar-absorbing façade can be further improved by the integration with other advanced technologies. A simple extension is the photovoltaic (PV) inclusion, for instance with the solar cells positioned at the structural frame outside the front glazed area. The electricity generation can be used to support the pumping power of the secondary water flow. This will not affect the overall water heat-gain performance as long as the glazed area is not shaded. Instead, there may be improvement on the thermal bridging condition of the structural frame, which often leads to additional air-conditioning load.

Another advancement lies in the use of nano fluid at the window cavity. This is able to increase the solar absorption capability of the liquid in the presence of invisible size of solid particles. Higher concentration of the nano particle will improve the heat absorption but at the expense of visual comfort and daylight transmission. On the other hand, the instability of the nano fluid like particle coagulation may limit the working life [6,7]. From the practicality point of view, this may not be a good design option in the near future.

IV. Conclusions

The global energy and environmental problems call for the better utilization of renewable energy in buildings, especially in the solar energy category. The novel solar-absorbing façade panel here proposed incorporates two recent inventions, namely (i) the water-filled double glazing with submerged heat exchanger, and (ii) the heat-pipe-ring embedded curtain walling. With an appropriate coverage of the new panels on the building envelope as a whole, and the appropriate ratio of the glazed area to the opaque area, this innovative façade is able to reduce effectively the solar transmission through the building envelope and to generate adequate hot water with excellent thermal efficiency.

Our numerical analysis shows that under the typical weather conditions of Hong Kong, the 50:50 in transparent to opaque area ratio is able to achieve a thermal efficiency of around 52.3% in useful water heat gain, and an overall electricity saving of around 32.8% in the air-conditioning plus hot-water systems operation. The above estimation is based on the mature technology at low cost. With the adoption of the advanced technologies and the relaxation in cost investment, even higher energy performance can be achieved. The final decision on the alternatives could be based on the results of cost-benefit analysis or life-cycle analysis on energy consumption, to be exercised case by case. After all, the energy payback and carbon payback evaluation can be more relevant for sustainable building development.

Acknowledgment

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About Authors:

New solar-absorbing façade with two recent inventions for green building applications in warm and hot climate.