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Conceptual Development of a Compact Unglazed Solar Thermal Facade (STF) For Building Integration

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Abstract

This research aims to develop an initiative modular unglazed Solar Thermal Facade (STF) concept initially for hot water generation to facilitate the integration of solar energy with buildings. The new STF concept is simple structure, low cost, and aesthetically appealing with easy installation but is expected to achieve the equivalent thermal efficiency as the conventional STFs. It delivered alternative design in terms of material, colour, texture, shape, size, architectural design, installation method, array connection, hypothetical system application, and solar coverage. Two common design variants i.e. (a) the STF cladding system and (b) the prefabricated STF wall system were described respectively for existing and new low-rise building typologies. Interaction of inclination, orientation, and insolation were discussed for the optimum STF position on the building. Four currently available methods for installation of such STF with buildings were summarized and three typical array connection methods were identified. The decentralized connection was recommended for different types of STF hot water systems. It is customary to design for a solar coverage of 50 to 60 percent for water heating in detached houses; in apartment buildings 30 to 40 percent are more commonly assumed. The concept design in this paper hereby illustrates the precedence for the hypothetical function by the creation of new ideas and also forms up the physical structure or operating principle for the investigations in near future.

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Keywords: Solar; Thermal façade; Concept design; Building integration

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1. Introduction

Solar thermal energy is one of the most promising renewable sources locally available for use in applications of building heating, cooling, hot water supply and power production. According to the vision plan issued by European Solar Thermal Technology Platform (ESTTP), by 2030 up to 50 % of the low and medium temperature heat will be delivered through solar thermal [1]. However, most solar thermal systems are currently applied in small-scale plants only. When they come to applications in large-scale space heating plants in urban networks, the insufficient suitable-and-oriented roof of most buildings may dictate the solar thermal implementation. It is therefore necessary to develop new solar thermal technologies with feasibility to be truly integrated with different building envelope components. Such requirement opens up a large-and new-market segment of the solar thermal systems for both new and existing buildings in need of energy retrofit actions and façade renovation. This will be especially considered for any future design solutions at district or/and city levels.

Solar Thermal Facade (STF) systems demonstrate a real sense of integration with building that can be potential solutions for the enhanced energy efficiency and reduced operational cost in contemporary built environment. There are extensive cutting-edge technologies and industrial products relating to STF [2, 3]. According their application functions, these STFs can be generally classified as (1) insulation based types; (2) solar thermal based ones; (3) solar photovoltaic/thermal (PV/T) based types. A few representative STF configurations are presented as follows. In terms of the insulation function, the STFs can be either constructed from two galvanized and coated steel sheets with an insulation filling (i.e. mineral wool, polyester, vacuum panel, aerogel granulate etc.) [4-7], or made up with ventilated air channels (or working with phase-change materials) to generate a thermal-insulating facade system [8-10]. In terms of the solar thermal collection function, the STFs are usually derived from the traditional glazed/unglazed flat-plate solar collectors or the evacuated tubes [2, 3], among which the most important element is the thermal absorber – made of a thin metal or polymeric plate coated with a selected coating material to maximize its solar absorption rate and minimize the infrared loss [11]. There are also some newly developed ones, such as isosceles trapeze shaped air heater [12], water film based STF type [13], loop heat pipe [14] and oscillating heat-pipe incorporated ones [15]. In terms of the hybrid solar PV/T collection function, most of the building integrated STFs' structural arrangements (known as BIPV/T) are formulated by incorporating additional fluid channel between the PV module and the building envelopes. These designs are often developed to cool down the PV modules, increase the corresponding electrical efficiency, and meanwhile make utilization of the waste PV heat [16-18]. On the other hand, great endeavors have also been made in commercial available STF devices, i.e. Nordic solar thermal copper façades by Aurubis [19], are available for adding to a rich palette of colors and surface textures.

Although the above mentioned work have achieved a remarkable R&D progress of STF, most the current available STFs can only work with the air during practical applications due to their inherent technical barriers, like: (1) bulky size or high weight with complex structures containing multiple heat absorbing tubes/channels and heat exchanging units; (2) relatively low solar efficiencies owing to less effective heat transfer from the absorber to the water pipes (or air tubes) in case of the promising sheet-and-tube structure; (3) less feasibility to be integrated with the building envelopes owing to the limited shape availability and the great thickness/weight; (4) high pressure drop that consumes much electricity to circulate the working fluid at a large-scale application.

As a result, this paper developed a novel compact solar thermal absorber working as the STF with internally extruded pin-fin flow channel suiting for the building integration. The proposed absorber concept is expected to overcome some of the above mentioned challenges remained in the STF research. The new STF concept is simple structure, low cost, and aesthetically appealing with easy installation but is able to achieve the equivalent or higher thermal efficiency as the conventional STFs [20]. A conceptual development of such a compact unglazed STF for building integration STF will be implemented in line with a series of design conditions in this paper. The overall research results would be useful for further design, optimisation, and application of such STF in the solar driven systems to offer hot air, space heating, agriculture/herb drying, increased ventilation, or even electricity.

2. Conceptual design

2.1. STF module configuration and its integration with building

The basic configuration of the STF module is presented in Fig. 1. The single-embossed panel is made up by two stainless steel sheets, one of which is extruded by machinery mould together to formulate arrays of pin-fin corrugations, while the another sheet working as the absorbing surface remains smooth and can be coated into optional colour or texture according to different requests. Such built-in absorber channel helps to eliminate the utilization of tubes and enables a high flexibility in size or shape. This can be conducted by tailoring metal sheets depending on various architectural and aesthetic requirements. Thus, it is much simpler, more economical, and aesthetically appealing with easy installation. And it is able to achieve the equivalent thermal efficiency as the referenced STF (such as the bionic one) [20]. There are also two fluid inlets at the bottom and two fluid outlets on the top respectively with the standard piping joints for a symmetrical fluid distribution. Such unique compact structure engenders not only high heat transfer performance owing to the finned absorbing surface and the crossflow over the pin fins but also great feasibility in assembly of either parallel or series flow pattern.

In contrast to traditional tubes attached to the absorber sheet, an internally extruded sheet welded together with another smooth sheet around the perimeter forms an absorber unity and channels. The fabrication prerequisite is based on the press forming technology for metal sheet, which is a well-established large-scale industrial process and is mainly applied for the production of heating radiators. As a result, it is expected that such STF could be produced at low cost since significant cost reductions could be achieved with the increased flexibility in industrial mass production. In addition, different arrangement and combination of the extruded pin-fin banks can form up different channels with the press forming technology and the channel structures can feature a high complexity without any additional costs. This enables high feasibility in channel structure at the boundary area in cases of various shape or size. So the combination of the extruded pin-fin banks and the press forming process could result in the possibility of developing a high-efficient, economical STF with high flexibility in architectural design. In practice, the proposed STF could be applied as either wall/roof or balcony external cover/claddings, which can be done by integration with supporting enclosure and insulation layer, as illustrated in Fig. 2 (a) and (b).

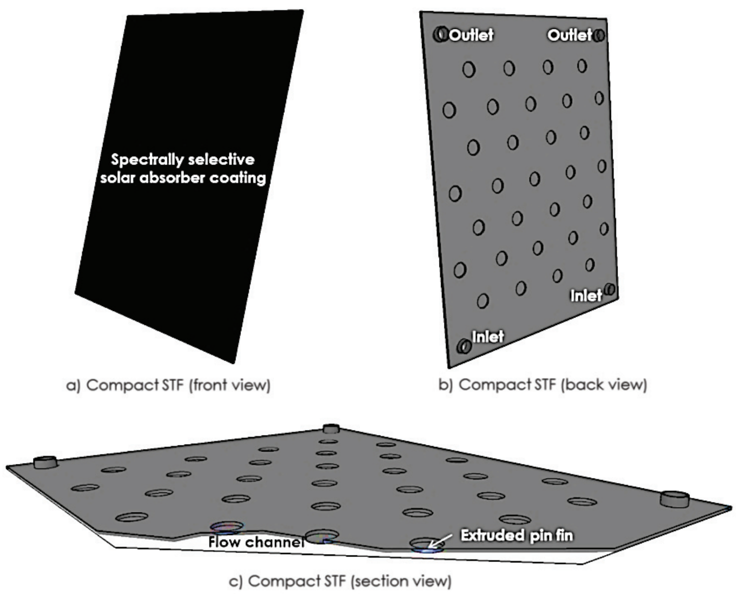

Fig 1 Concept design of the compact STF panel with internally extruded pin-fin channel

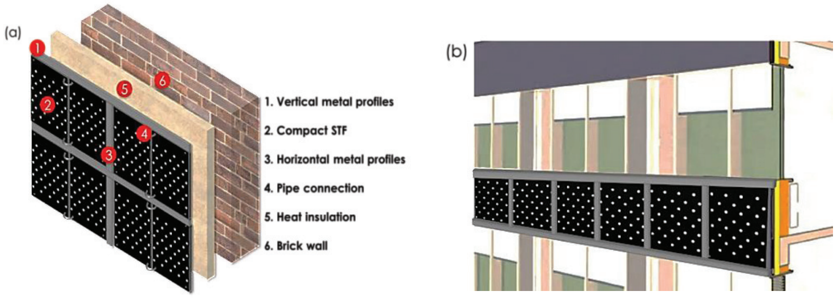

Fig 2 Schematic of compact STF integration with (a) wall; (b) sill

The STF could be made at standard modular size to form up the building external decorator for both horizontal and vertical installation, which is also beneficial to the architectural aesthetic of buildings. Each STF module is fitted with two tubular inlets and outlets that allow connection from module to module using the ease-off flexible couplers and pipes in either serial or parallel flow pattern. This creates a heating network to heat up the water gradually to the required temperature level. After completing the fixing-up and piping connection, the gaps between the adjacent STF modules could be sealed with a high standard sealant (e.g. stick rubber). All the connectors, fixing-up points and sealants are hidden behind side wings of the enclosures to avoid affecting aesthetical appearance.

2.2. Building installation method

Installation is a vital step that transfers STF into real multifunctional facade component and ensures the safety and durability for its operating. There are four currently available methods for installation of such STF with buildings, i.e. 1) anchor bracket and hang rail, 2) tongue and groove, 3) integral hanging rail and 4) the screw fixing as given schematically in Fig. 3. The anchor bracket & hanging rail and the tongue & groove belongs to the self-fixing method, which are suitable for the STF application in the form of cassette for large-scale envelope area. On the other hand, the integral hanging rail and the screw fixing can be categorized as the mechanical fixing methods, which are usually applied in the form of panel for small envelope area.

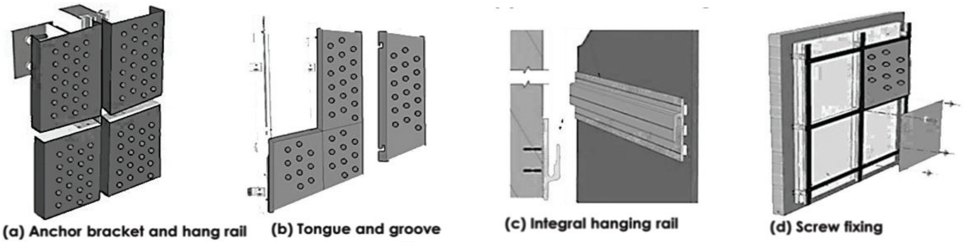

Fig 3 Several STF installation options using different jointing methods

Fig 4 Installation example of the proposed STF in an existing building

Fig. 4 especially illustrates an installation example in an existing building. The outdoor module of the STF is designed as a cladding system that can be attached onto an existing wall or roof with a firm, efficient and safe jointing. Similar to the cassette metal cladding system, the prefabricated outdoor module is an integral enclosure, commonly made of metal, wood or concrete, with reserved inlet and outlet. During the installation, a pair of tongue and groove is employed to form a negative jointing installation. Within facade construction, the groove supporting part would be firstly bolted into the facade structure (as process I). After that, the cassette module would be simply hold on with the fixed tongue component (as process II) and finally the module would be closely pressed downwards into the slots (process III) and fitted onto the supports.

2.3. Working principle of STF module

In operation, the STF works on the same principle as conventional unglazed solar thermal collectors, consisting of a series processes: 1) solar absorption and heat gain by STF smooth surface; 2) conductive and convective heat transfer caused by temperature difference between the STF smooth surface and the surrounding air or the working medium; and 3) thermal radiation exchange between STF and its surroundings. Thanks to a selective solar coating, part of the solar energy is optimally converted into thermal energy once it strikes onto the STF smooth surface. A working medium, in general a water-glycol mixture, passes through the compact fluid channel from the bottom inlets and attains the solar heat from the pin-fin banks and smooth STF surface directly (as indicated in Fig. 5). Afterwards, the generated thermal energy is output from the top outlets and further transferred as the useful energy to the heat circuit by a heat exchanger for storage or utilization. Finally, the returned working medium enters into the STF bottom inlets again to complete the circulation. In the meanwhile, the rest of solar energy is dissipated to the surroundings as the form of heat loss.

2.4. STF's material choice

Metal panels have already been developed for optimal heat exchangers in solar field. The initial design needs to pay additional spotlights on the possibility of compact dimension, fabrication, durability and the cost. Currently, the popular metals for piping and construction are stainless steel, aluminium, copper, and bronze as shown in Fig. 6. Proper STF materials should avoid much additional weight increase, thermal dilation and galvanic corrosion but with the superiorities in heat transfer performance and advanced manufactory technologies through processes like cutting, folding, pressing, and welding. According to such selection criteria, the detailed evaluation of these materials and the ultimate determination will be conducted in the following theoretical analysis part.

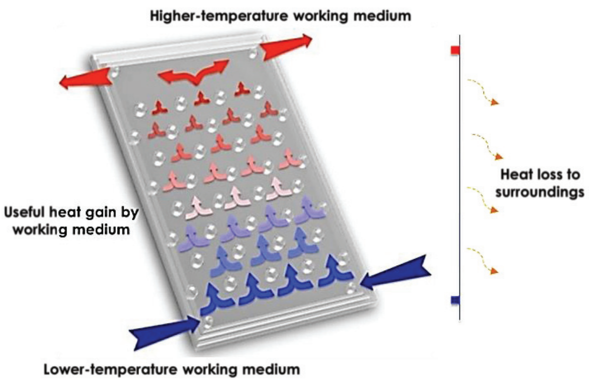

Fig 5 Schematic fluid flow of the STF

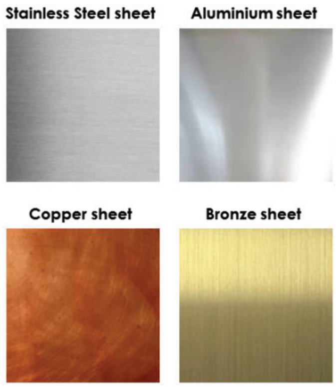

Fig 6 Potential metal materials of the STF

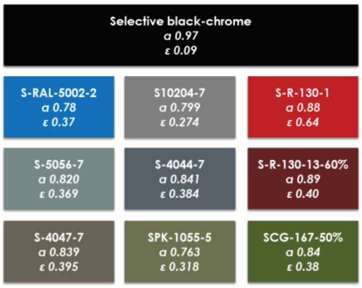

Fig 7 Colourful palettes for the STF smooth surface

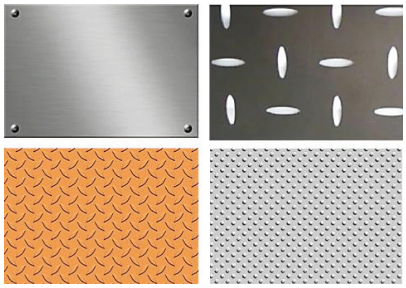

Fig 8 Texture options for the STF smooth surface

2.5. Colour and texture

Fig. 7 illustrates a large number of colourful palettes for STF smooth surface developed by typical selective black-chrome coating and the TISS paint [21]. Different absorptance (α) and emittance (ε) values characterize the various colours of the palette. It comprises both high and low efficiency shades, leaving to the architect and engineers with the choice of using a more or less efficient colour according to building and context specificities. The selection should be balanced in terms of the aesthetics and the energy efficiency criteria in order to maximize solar absorption rate and minimize the infrared heat loss from the STF. According to such selection criteria, the detailed evaluation of these colours and the ultimate recommendation will be conducted in the following theoretical analysis part. In addition to the high flexibility in colour options, the STF smooth surface could be design with infinite possibilities of textures to meet any architectural requirement, indicating in Fig. 8.

2.6. Shape and size

Apart from the flat-plate and rectangle shapes, the STF could be made into curved or polygon ones, as shown in Fig. 9. Potentially, such STF can be tailored depending on various architectural and aesthetic geometric requirements by cutting the metal sheets into different sizes. These variations greatly enhance the aesthetical effect of buildings, thus enabling the STF meeting a diverse range of architectural and aesthetical needs.

2.7. Architectural design of STF for building integration

(1) Design for low-rise building typologies

Fig. 10 presents two common design variants of the proposed STF respectively for existing and new low-rise building typologies, i.e. (a) the STF cladding system and (b) the prefabricated STF wall system. The STF cladding system is similar as the rainscreen cladding system, which is particularly developed for the low-rise building or facade renovation.

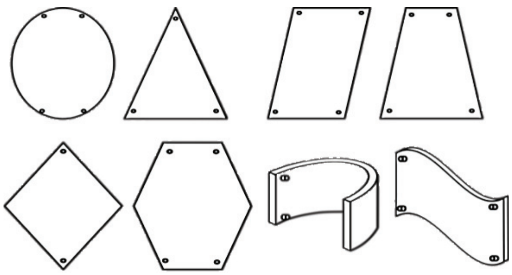

Fig 9 STF claddings for shape/colour changes to meet architectural and aesthetic requirement

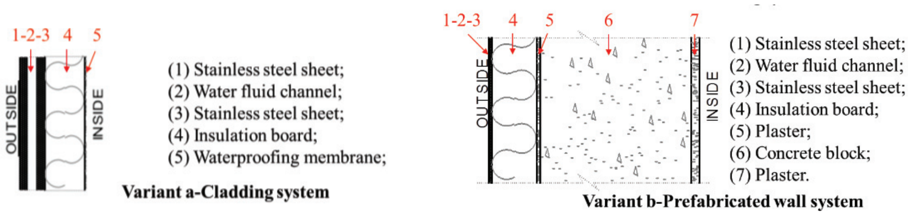

Fig 10 Schematic designs of STF for low-rise building typologies

This STF variant can be mounted onto the original wall system for the purposes like, preventing the rain, offering thermal insulation, reducing excessive air leakage, and carrying wind load. The prefabricated STF wall system is recommended for the new buildings in order to reduce the heat loss from internal space. It is a revise of the STF cladding system, consisting of extra layers of thermal mass and facade finish.

(2) Design for mid/high-rise building typologies

Fig. 11 generally illustrates eights design types of the proposed STF integration with different building typologies. In Type (1), the proposed STF is integrated on the opaque solid wall, while in Type (2). the STF is applied in an alternating pattern with the curtain walling system. Type (3) and Type (4) are similar to Type (1) by integrating the STF around a punched/strip window. In Type (5), the STF is installed as the balcony component. The proposed STF can also be used as local shading due to its compact structure. In such a case, Type (6), Type (7), and Type (8) present examples of self, horizontal, and vertical shading respectively.

2.8. Inclination, orientation and insolation

Fig. 12 demonstrates the interaction of inclination, orientation, and insolation. The values of global radiation energy are influenced by the inclination of the receiver surface. The amount of energy is greatest when the radiation hits the receiver surface at the right angle. In the northern hemisphere, an orientation towards the south is ideal. Subject to the angle and orientation of a surface, the level of insolation – relative to a horizontal area would reduce or increase. A range can be defined between south-east and south-west and at angles between 25 and 70°, where the yields achieved by a solar thermal system are ideal. Greater deviations for systems on vertical walls can be potentially compensated for by correspondingly larger collector area. So the vertical STF can possibly produce more solar heat than that on the other building components due to the potential availability of larger solar collecting area. Moreover, the vertical STFs are less sensitive to the weather conditions, such as dust, rain and snow [22]. As a result, the optimum installation position for the STF, if from the energy yield point of view, should be depending on different building scenarios or limitations, rather than particular one.

2.9. STF array connection

Owing to the low outcome temperature of the unglazed design, such STF produces the low quality of the solar energy so that a large collection area of STF arrays may be required for different energy load. There are typically three hydraulic array connection methods, like in series, in parallel, and in combined patterns.

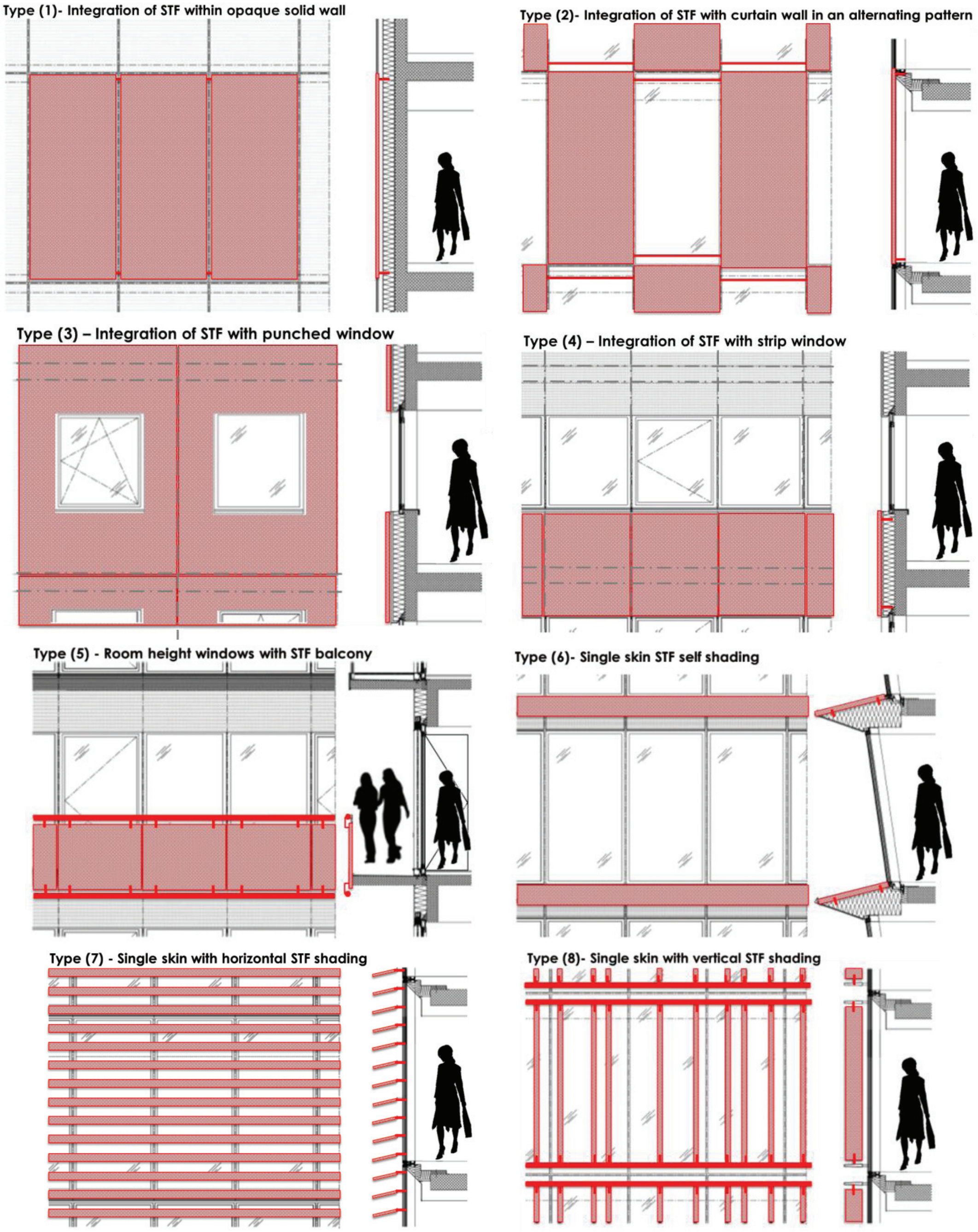

Fig 11 Schematic design of STF for mid/high-rise building

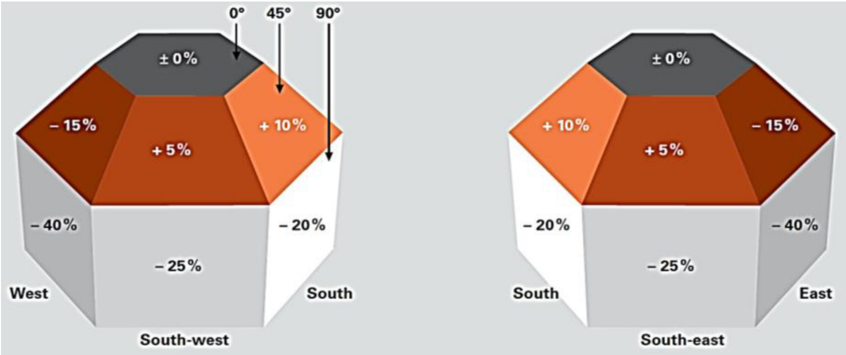

Fig 12 Deviation from global radiation

In case of series connection, all the STF modules are connected successively as illustrated in Fig. 13. The type of connection ensures a uniform flow for a higher solar yield; however it should be in proportion to the number of modules to take away all the arising solar heat. Another feature of this type connection is that the flow resistance increases with the number of modules, therefore the number of connected modules are limited by pumping power [23]. In contrast, the parallel connection is well designed at inherently balance, lower pressure drop, and easy drainage. Fig. 14 illustrates four different parallel arrangements, i.e. the external Types (a)/(b) and the internal Types (c)/(d) [24]. The external type is connected individually to the manifold. As a result, each module is independent that provides high flexibility in maintenance. Such parallel connection is frequently used in small projects [24]. The internal type is connected side by side of each module form a continuous supply and return manifold. Because of the integral manifold pipe, it requires less fittings, insulation and support accessories. As a result, it is generally more accessibility for worksite installation and more economical for a large number of STFs installation. Such connection type also eliminates external manifold that is associated with extra heat loss and exposure damages.

For large-scale STF application, a combination of series and parallel connection should be considered, as illustrated in Fig. 15, since both array hydraulics and installation quality are equally important [23]. In order to achieve uniform flow through the module arrays at low flow resistance (low pumping power), empirical design recommends either (a) installation of balancing valves in the return manifold or (b) application of long reversed return manifold.

2.10. Decentralized connection design

In cases of multifamily household or mid/high-rise application, it is suggested to install the proposed STF system close to the end user as decentralized connection rather than the centralized connection. As a result, the system loop does not need to run though the entire building that would save considerable piping and reduce large amount of flow resistance/heat loss than that in the conventional centralized system. Fig. 16 presents a typical concept design of the STF system application in a multifamily household for hot water and space heating delivery. The STF modules are connected in decentralized arrangement, which allows the archived low-and-medium-temperature fluid to be delivered into the end user and therefore maximally reduces the sensitive transportation losses.

2.11. Hypothetical system design for the hot water generation

Fig. 17 illustrates different types of STF modules for hot water generation. All these types are featured of the internal solar heat exchanger arranged at the bottom position inside the water tank. Type (a) is the most cost-effective design with least components and lowest system pressure loss, which is usually applied in areas with abundant annual solar radiance resource, or in a dual-mode operation for preheating purposes. Type (b) improves the overall system performance by a bypass circuit design that helps to prevent the reversible heat transfer form water tank to the unglazed STF modules.

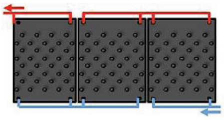

Fig 13 Series connection

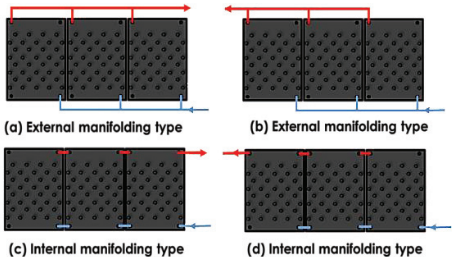

Fig 14 Parallel connection

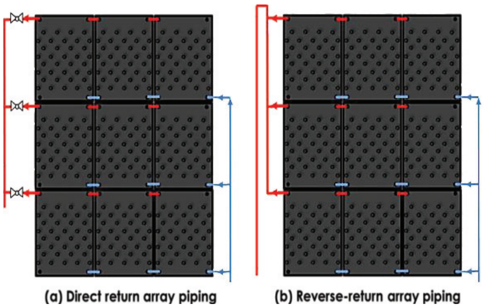

Fig 15 Combined connection

In Type (c), an auxiliary heating circuit is supplemented in conditions of insufficient solar radiation. Similarly, Type (d) has two internal heat exchangers and feeds water tank with a tee joint at two different heights. It has advantage in rapid reaching of useful temperatures in the standby area with increased system efficiency. For auxiliary heating devices, for instance conventional gas/electric boiler and heat pump, can achieve relatively high overall efficiency, while the electric heater superiors in small heat storage loss, quick heating response and compatible system occupancy volume. It thus needs to select appropriate auxiliary heater depending on specific scenarios.

2.12. Solar coverage

Solar coverage is an essential variable required for designing a solar thermal system, which states the ratio of the energy supplied by the solar thermal system to the overall energy load. Solar coverage takes into account the heat losses from system components like water tank, pipe, valve, heat exchanger etc. The higher the solar coverage results in the greater the savings in conventional energy, shown in Fig. 18. But when such STFs are further applied for large-scale projects, the thermal efficiency may drop depending on the scalability due to the unavoidable rising temperature differential between STF and ambient temperature during the system circulation. As a result, the higher the solar coverage (scalability) means the lower the specific yield (efficiency). So a good compromise between solar coverage (scalability) and solar yield (efficiency) must be found for each system during the facade integration design. It is customary to design for a solar coverage of 50 to 60 percentages for water heating in detached houses, meanwhile 30 to 40 percentage in apartment buildings [22].

According to authors' preliminary research results [20], the STF's nominal thermal efficiency was about 63.21% at the given the baseline testing condition, is able to achieve the equivalent thermal efficiency as the referenced STF (such as the bionic one). It needs to be addressed that this paper is only used to prove the concept at current stage. When such STFs are further connected into arrays for large-scale application, the thermal efficiency may drop depending on the scalability due to the unavoidable rising temperature differential between STF and ambient temperature during the system circulation. As a result, the higher the solar coverage (scalability) means the lower the specific yield (efficiency). So a good compromise between solar coverage (scalability) and solar yield (efficiency) must be found for each system during the facade integration design.

3. Conclusion

This paper described the compact unglazed STF concept for hot water generation along with the related working principle. The new STF concept is simple structure, low cost, and aesthetically appealing with easy installation but is able to achieve the equivalent thermal efficiency as the conventional STFs. In practice, the proposed STF could be applied as either wall/roof or balcony external cover/claddings.

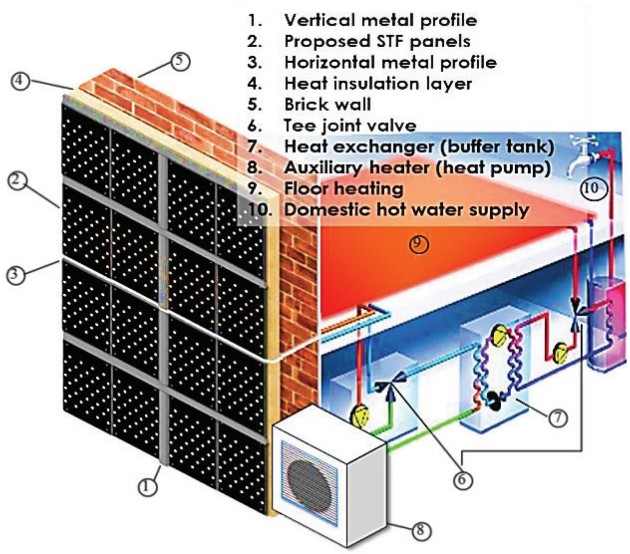

Fig 16 Conceptual design of the facade application with the proposed STF

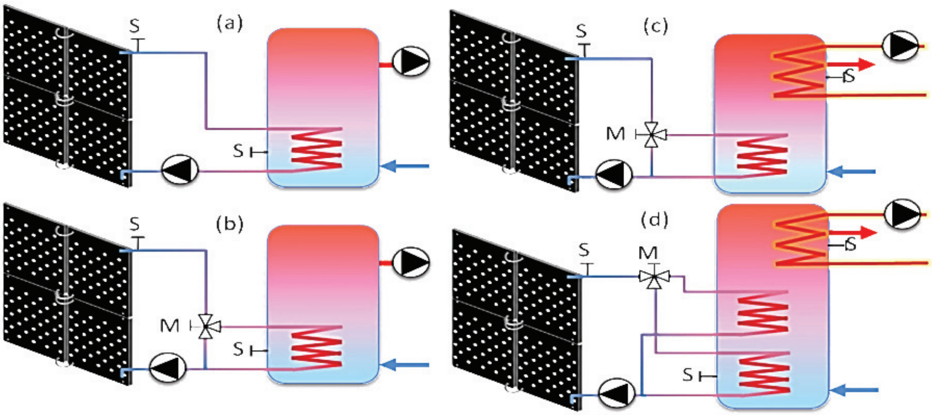

Fig 17 Possible variants of the compact STF system connections

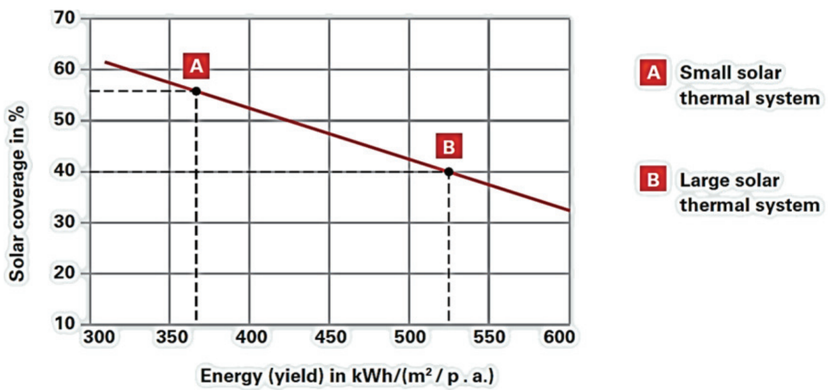

Fig 18 Solar coverage for hot water generation [22]

It also delivered alternative design in terms of material, colour, texture, shape, geometric size, architectural design, installation method, array connection, hypothetical system application, and solar coverage. Two common design variants i.e. 1) STF cladding system and 2) prefabricated STF wall system were described respectively for existing and new low-rise building typologies while eights design types of the STF integration with different building typologies were illustrated. Interaction of inclination, orientation, and insolation were discussed for the optimum STF position on the building. Four currently available methods for installation of such STF with buildings were summarized and three typical array connection methods (series, parallel, and combined patterns) were identified. The decentralized connection is also recommended. Finally, the customary solar coverage is concluded with 50 to 60 percent-ages for water heating in detached houses, and 30 to 40 percentages in apartment buildings.

It needs to be addressed that this paper only aims to prove the concept at current stage while further technical and socio-economic analysis will be conducted during following research. When such STFs are further connected into arrays for large-scale application, the thermal efficiency may drop depending on the scalability due to the unavoidable rising temperature differential between STF and ambient temperature during the system circulation. As a result, the higher the solar coverage (scalability) means the lower the specific yield (efficiency). So a good compromise between solar coverage (scalability) and solar yield (efficiency) must be found for each system during the facade integration design.

The concept design hereby illustrates the precedence for the hypothetical function by the creation of new ideas and also forms up the physical structure for the investigations in following research, such as system performance evaluation, economic and environmental assessment.

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