Sixth International Conference on Thermal Engineering: Theory and Applications
May 29-June 1 2012, Istanbul, Turkey

In situ measurements of the thermal performance of several unglazed transpired solar collectors in Canada

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Abstract

To capture solar energy for heating purposes, one of the promising technologies is the Unglazed Transpired Collector (UTC). UTC consists of a perforated surface heated by direct exposure to the sun. On top, a fan draws the air from the space behind the collector causing a depression bringing the outside air into the plenum through the holes. The heated air can then be used for building heating, as pre-heated air. Some UTCs have demonstrated an efficiency of 50% with high wind and 70% without. While the efficiency of opaque UTCs is already impressive a new type of UTC has recently become available on the market. These new UTCs use a transparent cover to solar radiation. In this configuration, the collector is now the inner wall itself. The transparent panel absorbs little solar energy, which reduces its equilibrium temperature compare to an opaque collector. As a consequence, there is even less losses by conduction, convection and radiation than for a conventional UTC. Another advantage of the transparent collector is that it can be easily integrated to any architectural style and window circumvention. Nevertheless, there is little experimental data outside the laboratories. This is why the t3e research chair has initiated an experimental research program on various transparent UTC installations to assess their performance in real operative conditions.

Keywords: solar energy, unglazed transpired collector, full scale experiment

1. Introduction

1.1. The need for energy efficiency in buildings

Energy efficiency is a key tool to tackle two of the biggest challenge facing humanity: climate change and energy scarcity. Transportation is often singled out as the main target for energy efficiency. However, building industry has an even larger energy and environmental footprint as it is one of the human activities with the largest environmental impact. As noted by Dixit et al. [1], the construction industry depleted two-fifths of global raw stone, gravel, and sand; one-fourth of virgin wood; and it consumes 40 percent of total energy and 16 percent of fresh water annually [2-8]. These figures are more or less similar in any developed country. Indeed, for OECD countries, energy consumption by buildings varies between 25%–50% of total energy consumption [9], whereas it is closer to 50% in the European Union [10].

In these conditions, building industry is an obvious target for energy efficiency. This is the rationale behind the European Union Directive on Energy Performance of Buildings [11] that requires member states to implement energy efficiency legislations for buildings, including existing ones with floor areas over 1,000 m^2 that undergo significant renovations. The French legislation [12] specifies that by January 2013, any new building will have to consume less than 50kWh·$m^{-2}yr^{-1}$. By 2020, all new buildings will have to be at least net zero – that is involving a net consumption of 0 kWh·$m^{-2}yr^{-1}$ – or better, that is globally producing energy [12]. In a similar way, the Swedish government promulgated a Bill on Energy Efficiency and Smart Construction, to reduce total energy use per heated building area by 20% by 2020 and 50% by 2050, using year 1995 as the reference [13]. Such ambitious goals in energy efficiency improvements raise the key issue of the efficient allocation of resources.

1.2. The Unglazed Transpired Collector

One of these enabling technologies is the Unglazed Transpired Collector (UTC). The UTCs consist of a perforated surface, hereafter the "cover plate", directly exposed to the irradiation, G_T, from the sun (Figure 1).

The solar irradiation is either absorbed by the cover plate in the case of an opaque collector or most of the irradiation is transmitted through this cover plate when it is made of a transparent material. In the latter case, most of G_T, impinges upon the back plate (which is the original wall of the building). Of course, when the cover plate is opaque, its temperature, T_{cp}, increases way above the

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ambient temperature, T_{amb}, while when the plate is transparent, T_{cp}, increases a lot less.

In both cases, on top, a fan draws the air from the space behind the collector (plenum) causing a depression. This low pressure sucks the outside air laying in the boundary layer close to the wall, into the plenum, through the perforations.

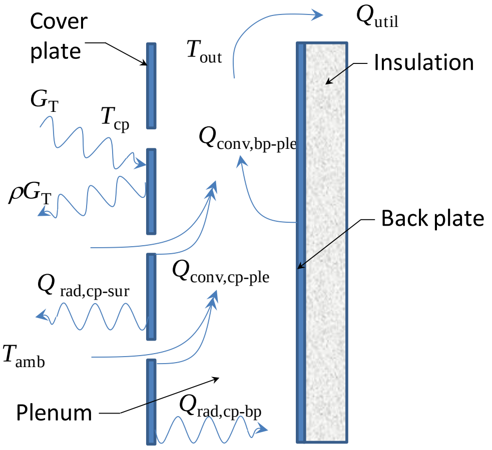

Fig. 1. Energy balance on a UTC.

Whether the cover plate is transparent or opaque, the objective of the UTC is to maximize Q_{util} while keeping the fan power to a minimum. Another objective is to lower the production cost.

A great advantage of UTCs is that they can be easily integrated to a building since they replace the conventional cladding. Only an additional bypass on the ventilation system is needed for summer operation. As a consequence, the costs are minimal and the return on investment can be very short especially for the new buildings or when they are used as an alternate replacement for the aging existing cladding.

2. Energy balance and efficiency of the UTC

The important variables here are the ambient temperature, T_{amb}, the cover plate average temperature, T_{abs}, and the outlet temperature, T_{out}, that will be used to compute η_{coll}, the efficiency. The mass flow rate is also a predominant variable that must be measured.

To permit an analysis of the UTC's efficiency, several assumptions have to be formulated: (1) the mass flow rate through the perforation is assumed to be homogeneous; (2) the reverse flow across the perforation is neglected; (3) the absorber plate is considered to be diffuse and gray; (4) losses along the plenum edge are neglected; (5) the absorber and back plate temperatures are assumed to be isothermal throughout their respective surfaces and thicknesses; (6) convection losses from the plate to the environment are considered negligible; (7) air thermophysical properties are assumed to be constant and evaluated at an average temperature $(T_{amb}+T_{out})/2$; (8) the back plate is perfectly insulated. These assumptions are consistent with studies carried-out earlier [14-16] and are discussed in [17].

Overall, the thermal measurements allow computing the thermal power of the unit which is simply obtained from the incident solar radiation minus all types of heat losses. Strictly, one could establish an energy balance on the cover plate, on the plenum air, and on the back plate (which is neglected here). These balances call for the evaluation of radiative and convective heat fluxes. But here, the sole interest is the efficiency of the collector defined such as:

$$\eta_{coll} = \frac{\dot{m}_{out} c_p \left(T_{out} - T_{amb}\right)}{G_T A_{coll}} \qquad (1)$$

The efficiency is then the ratio of the useful recovered power, Q_{util}, to the total solar power input on the surface.

3. Two types of UTCs: opaque and transparent

3.1. The opaque UTC

Studies of UTC started in the late 80s [18]. Soon it was demonstrated that these collectors were more efficient than classical flat plate solar collector. One of the first experimental studies was carried out by Carpenter and Kokko [19] who studied three facilities with three different solar technologies. The first was a set of transparent plastic plate to protect a steel absorber plate insulated with glass fiber. The second was to paint the south side with a dark color and collect the heated air by natural convection to the top of the wall. The latter system was a UTC. The results and their extrapolation showed that the UTC was the most efficient systems. Later, the same group [20] analyzed the performance for a factory where an UTC was installed. They showed that this design increased the efficiency by 16%. The UTC demonstrated an efficiency of 50% with high wind and 70% with no wind.

This technology has been commercially distributed in Canada and worldwide by Conserval. As of 2010, Conserval Engineering [21] claims that it supplied and designed over 3 million square feet (278 000 m^2) of its systems in 30 countries.

Hollick [22] demonstrated from study results of various facilities in Ontario, Canada and in Germany that the efficiency results given by the "National Solar Test Facility" underestimated the large plants efficiency because of the side effects and the fact that they recovered the heated air from the ground in front of the wall. Later, the author [23] described two implementations:

- The first in Windsor, Canada, where the height of the UTC was the highest known at the time. This height induces a strong chimney effect and return on investment (ROI) was estimated at 6 years.
- The second implementation was a Canadair building in Montreal, Canada, and had an immediate ROI because the work had cost the same price as the facades to be replaced. Thus, the energy and economic gains were 8.3 GWh and $CAN180,000 per year.

Globally, UTCs reportedly offer the lowest cost and highest efficiency (60–75%) for air heating [15].

With reference to figure 1, the principle behind the performance of the opaque collector is the following: (1) the impinging solar irradiation G_T, is mostly absorbed by the cover plate; (2) only a small portion of G_T, is reflected back to the surroundings; (3) the cover plates warm up to temperatures that could reach 70^{o}C; (4) the external boundary layer is sucked into the perforations (this is the major contribution of the system as some heat is also recovered from the inner convective heat transfer); (5) the cover plate radiates back into the surroundings.

3.2. The transparent UTC

While the efficiency of an opaque UTC is already impressive, a new type of UTC has recently become available on the market. These new UTCs use a cover plate which is mostly transparent to solar radiation. For this configuration, the energy collector is now the back plate itself. The transparent cover plate absorbs little solar energy, which reduces its equilibrium temperature T_{cp}, compared to an opaque plate. As a consequence, there is even less losses by conduction, convection and radiation than for a conventional UTC. The ideal cover plate should have a transmissivity of near one for solar radiation (for which the maximum emission according to Wien's law is at about $\lambda = 0.5$ μm) and near zero in the near infrared (at about 8.2-8.9 μm peak as the back wall reaches about 70^{o}C) as the radiation emitted by the back wall should ideally be trapped into the plenum.

Another advantage of the transparent collector is that it can easily be integrated to any architectural style and window circumvention.

A commercial version of these UTC, Lubi™, has been patented by Enerconcept, a partner of t3e research chair. This panel has been tested by the National Solar Test Facility (NSTF, Mississauga, Ont, Canada), The NSTF tests and rates solar technologies under controlled temperature/sunlight/wind condition. In these tests, the Lubi™ provided up to 80.7% peak heating efficiencies.

The tests indicated that the Lubi™ performance should be maintained over a wide range of air flow rates. Whereas traditional solar air collectors, glazed or not, suffer from a loss in performance with air flows lower than 100 $m^3/h/m^2$, this remains as high as 55% with air flows as low as 40 $m^3/h/m^2$. This allows for a substantial temperature increase as high as 45°C and a maximum output of 800 W/m^2. Its performance is also insensitive to wind speed lower than 3 m/s. The Lubi™ could be installed a distances ranging from 5 to 25 cm from the wall, depending on the airflow pattern, number of air intakes, wall surface and wall geometry.

This could allow it to fulfill applications ranging from pre-heating outdoor air to supplemental heating of facilities, depending upon application, geography and weather conditions.

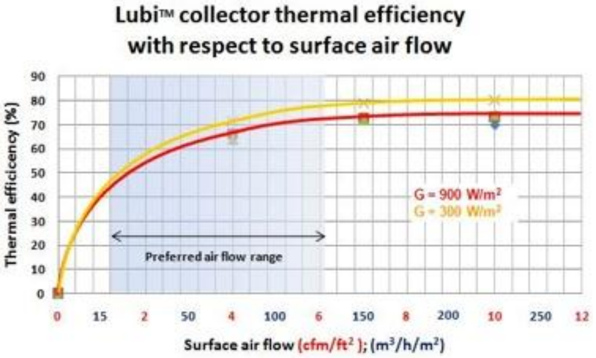

Fig. 2. Lubi™ efficiency vs air flow.

Indoor testing is indeed mandatory as the environment is totally controlled and parametric studies can be carried out. This provides answers to the questions pertaining to performance improvement. Nevertheless, what is needed by the customer who eventually buys the system is an assessment in real conditions. The basic question is what will be the payback period?

Tests need to be performed on large scale system as some other factors might affect the performances as demonstrated by Hollick [22] for the classical (opaque) UTC.

In this context, Enerconcept decided to call upon the t3e research chair to carry-out infield measurements over a period of one year for two different applications.

3. Implementation testing

For global yearly performance calculations purposes, the Lubi™ systems have been equipped with sensors to measure their instantaneous and average efficiency outside the laboratory in three different environments: *Centre des technologies du gaz naturel*, *Centre hospitalier universitaire de Québec*, and *Les résidences étudiantes 4* of *École de technologie supérieure.*

For all sites, the instantaneous power production of the solar collector, Q_{util}, is estimated simply by the product of the mass flow rate measured at the exit of the plenum where hot air is directed in the building, $\dot{m}_{out}$, specific heat evaluated at the exit temperature in the plenum T_{out}, c_p, and temperature difference, $\Delta T = T_{out} - T_{amb}$:

$$Q_{util} = \dot{m}_{out} c_p \left(T_{out} - T_{amb} \right) \quad (2)$$

The irradiation is both estimated for tables and measured with a Kipp & Zonen CMP11 pyranometer (±7 W/m^2) involving a 32 junctions thermopile.

3.1. Centre des technologies du gaz naturel

The first experimental set-up has been installed at the *Centre des technologies du gaz naturel*, in Boucherville, Canada. This set-up consists of 4 UTC: one opaque (used as a baseline) and 3 Lubi™. Each solar collector measures 4m × 5 m and all are located side by side on the same south-west wall of the building. The three transparent UTCs are mounted in front of a brick wall, white steel cladding and black steel cladding, respectively. These three configurations allow the direct comparison of the performance of the Lubi™ in typical retrofit applications, where the transparent UTC is placed over an existing cladding.

No information is available on the internal temperature in the collector or the airflow inside them. Nevertheless, some discrepancies with the laboratory measurement were observed. Due to the limited instrumentation available the causes of this difference cannot be précised.

3.2. Centre hospitalier universitaire de Québec

To assess its real life performances, the Lubi™ system installed at the CHUQ (Centre hospitalier universitaire de Québec) hospital was instrumented. This system is used to reduce the large heat loads due to the local cold climate (5200 heating degree-day).

This system is used to pre-heat air for the two 100% fresh air ventilation systems of the hospital. These two systems have an air flow rate of about 6 m^3/s each. The solar wall has a total area of 260 m^2: 185 m^2 of Lubi™ collectors and the balance is constituted of dampers and canopy. The solar collector is located on two walls of the mechanical room on top of the building. These walls are oriented West and South, with 80% of the collectors installed on South side.

The performance of this type of equipment is highly dependent to the geographic position and sunshine hours. According to the RETScreen database, a vertical solar air heater system with an orientation 15° from South direction receives between 2.40 and 5.25 kWh/m²/day. During the heating season, usually from October to May, it can be expected that the total energy received by the collectors is about 170 MWh.

The main objective of this experimentation is similar to the preceding one: to measure the actual energy captured by the system to determine its performance under real operational conditions. The difference here is that it is not an external bench but a real large application Energy production of the solar collector is integrated for the upcoming year

Mass flow rate is fixed by design, while the temperature difference is measured with two thermocouples. Due to building accessibility constraints, the irradiation will be obtained from a local pyranometer located at the Quebec international airport situated 8 km WNW from the hospital. Supplemental data will be gathered on the ventilation system motors to measure the addition charge caused by the solar collector.

At the moment of writing this communication, the first winter of operation of this system had yet to be complete.

3.3. University residence

A student residence building of the École de technologie supérieure in Montréal is heated by two HVAC systems with an air flow rate of 1.9 m^3/s each. Fresh air input of the systems will be preheated respectively by two vertical solar collectors placed in facade and two horizontal collectors placed on the roof. They are facing straight south. Those are large collectors (1 m × 21 m) and their slenderness will amplify the impact of the geometry and, for the vertical panels, the convection.

Unlike the previous installations, these two systems will be fully instrumented. Two panels, one of each orientation, will have 68 thermocouples to measure the temperature gradients. In the panels themselves, temperature in the front and back of the transparent panel and the wall surface will be measured. Anemometers will be used to trace the air displacement inside them, while a pyranometer will be used to track the variation of the solar insolation.

At the moment of this writing, these collectors are still in the design phase. Authorizations from the city of Montreal are needed to proceed. If the planning schedule is respected, these systems are expected to be operational for the winter 2012-2013 heating season.

4. Conclusion

The transparent UTC is one of those emerging technology that could help to meet the challenging environmental and energetic goals of the 21th century. Nevertheless, there is little experience with this new technology. The testing program described here aim at reduce the uncertainties related to this new technology.

These systems are now in the implementation phase and their first results will be presented at this conference.

Acknowledgments

The authors would finally like to thank the partners, Enerconcept and Ecosystem, of the Industrial Research Chair in Energy Technologies and Energy Efficiency and the Natural Sciences and Engineering Council for funding the research group.

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