Review of Unglazed Transpired Collectors (UTCs)

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Abstract

Today, new technologies are developed to integrate solar collectors into the building envelope. Among these technologies, solar energy harvesting produces either electricity or heat. The proposed review covers the latter approach to heat air. This paper aims to review the remarkable development of the air heating technology, specifically using unglazed transpired collectors. Successively reviewing theoretical studies, numerical studies, experiments, implementation studies, and applications, it demonstrates the different existing physical phenomenon, the design guidelines and behaviour that can be expected. Each section highlights the development avenues and the points that require further investigations.

Keywords: Unglazed, Transpired, Solar collector, air heating, Thermal solar collector.

Introduction

To reduce the buildings energy consumption, two of several solutions are to produce electricity through photovoltaic (PV) cells, or to collect solar heat. Solar heat collectors mainly consist of a surface heated by solar radiation and a fluid, be it liquid or gaseous, convected behind this heated surface, collecting the heat and carrying it where needed. Solar air collectors have the advantage to be almost maintenance free and not to suffer leakage as the fluid is not a contaminant (unlike the water-

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glycol mixture commonly used into cold climates) and pressure differences are very low. Through the years, numerous solar air collectors were developed. From these, Unglazed Transpired Collectors (UTCs) emerge as a simple and yet efficient technology. Figure 1 schematically describes the principles of the UTC. In this figure the fan diameter is much smaller than the duct diameter.

Figure 1. UTC schematic

The UTCs consist of a perforated surface (solar collector, Fig.1) heated by direct exposure to the sun. The space behind the collector through which air is collected vertically into the building is called the plenum. On top, a fan draws the air from the plenum causing a depression leading the outside fresh air into the plenum through the perforations. Passing through the holes of a heated surface causes the outside air to be heated by convection. The heated air can then be used for building heating, as pre-heated air or for any process as crop drying. This paper aims to review the scientific developments of UTCs since the late 80s when Christensen *et al* [1] compared three heating systems, one of which was an UTC, to the beginning of 2012. It is structured into theoretical studies, numerical studies, experiments, implementation studies, and applications.

1. Theoretical studies

Kutscher *et al* [2] made a heat balance on a UTC and compared their analytical results with an experimental set-up. They showed that the efficiency, define as the amount of energy recovered by the air divided by the total irradiation received by the collector, was little affected by wind when using large suction velocities (about 0.05 m/s). If suction decreases, efficiency decreases accordingly since the collector temperature increases and it becomes more sensitive to wind. They also suggested that a selective coating would improve performance. Later, the same authors [3] analyzed UTC thermal losses. They showed that natural convection on the outside of the collector can be neglected and confirmed the results of their previous work that wind velocity effects are important with low suction velocities. This analysis is limited to a laminar external flow parallel to the UTC and homogenous suction through the holes.

Hollands [4] conducted a literature review where he described the operation of UTC, then focused on the energy balances, only to look at the suction phenomena and flow uniformity. He concluded that radiation losses from the UTC to the environment are essentially the only mechanism for heat loss (no natural convection on the outside). He indicated that even without selective coating, the collector performance is considered high but he did not provide any quantitative result. Using a selective coating might be interesting if one seeks to raise the air temperature 20 to 30°C above the outside level. This can also be achieved by reducing the suction velocity. However, this solution can lead to poor efficiency and flow reversals at top of the plenum in cases for which the air intake is a the top of the collector.

Biona *et al* [5] investigated the correlations and analysis of various authors to define the effectiveness (as the temperature difference between collector outlet and the ambient divided by the temperature difference between the collector and the ambient) and efficiency of collectors. They gave an example of application of these relations for collector design used for drying. However the authors did not discussed the results.

Motahar and Alemrajabi [6] conducted an exergy analysis of UTC. Using a steady state model, they performed an optimization procedure taking into account the hole diameter, the spacing, solar radiation, and suction velocities. This procedure showed that the exergy efficiency reaches a 2.28% maximum. The most influential parameters were the radiation and the perforation parameters. Increasing suction was found to reduce exergy performances.

Gao and Fang [7] developed a mathematical model based on a heat balance. They noted that radiation and airflow have a strong effect on collector's efficiency. Absorptivity has a greater effect than emissivity on the heat recovered. As expected, the emissivity has more effect at higher outlet temperatures: for an emissivity going from 0.2 to 0.9, the heat output is reduced about 14% for a 30°C outlet temperature and about 45% for a 50°C outlet temperature.

Theoretical studies showed that UTC could reach 80% efficiency when the air suction is about 0.05 m/s. At this speed, the collector is not wind sensitive. Radiation is the main mechanism of heat loss. Correspondingly, when reducing suction, the UTC becomes wind sensitive, the plate temperature rises, efficiency drops, radiation losses rise. This confirmed previous acknowledged results [2].

2. Numerical studies

Christensen *et al* [1] compared the costs and performance of four solar systems with TRNSYS: a conventional integrated collector storage, that serves as a reference, an evacuated integrated collector storage, an unglazed heating water system, and finally an UTC. He showed that compared to the reference, UTC have the greatest reduction in operating cost, up to 70%. The study also describes the limits and preferred applications of the various systems.

In his PhD thesis, Kutscher [8] studied in depth the phenomena of flow and heat exchange around the holes using a 2D model implemented within FLUENT CFD software. He showed that the heat exchange takes place mostly in front of the holes. He also highlighted the need to use the logarithmic mean temperature to calculate the efficiency of the collector. These simulations also showed heat exchanges in the hole itself, on the back surface of the collector and it accounted for the wind effects.

Cao *et al* [9] conducted a numerical study for a wall with slots. They established a correlation based on geometric parameters, the plate conductivity and the air velocities to determine the effectiveness of the collector. They showed that three factors accounted for approximately 90% of the variability in efficiency. These factors are respectively a) the ratio W/L (slot width over the distance between the slots), b) t/L (plate thickness over the distance between the slots) and c) A_d (plate conductivity time plate thickness over air conductivity time distance between the slots). The heat transfer occurring in the slot is up to 20% of the total heat transfer.

Gunnewiek [10] conducted a numerical study to characterize the 3D airflow in the manifold. He identified six physical and geometrical parameters that conditioned the flow (the height of the collector, the absorptivity, the apparent heat loss coefficient, the average suction velocity, the plenum aspect ratio (height/thickness), and the hydraulic impedance of the collector). Then, he studied the effect of each factor under conditions of weak to strong suction, and no wind to strong wind. Buoyancy creates a chimney effect that combined with the fan suction are the flow driving factors. The resisting factors are the air viscosity, the fluid acceleration, and the collector shape. An important collector height and/or high absorbtivity accentuate the chimney effect and reduce the need for suction. The increase in aspect ratio and impedance slows the movement. The author identified and described flow regimes led by the chimney effect and the fan suction. He showed an unexpected effect of heat absorption behind the plate. He noted that the wind effect is important at low suction. He defined a ratio of pressure difference ($\Delta P_{out}/\Delta P_o$ determined from the outside air column and the pressure divided by the pressure drop across the plate when uniform flow) whose value predicts the reversal of flow and pressure drop. Gunnewiek *et al* [11], building on this model [10], proposed a 2D model that does not take wind effects into account. They showed that the nature of the velocity profile depends strongly on the fact that the flow is either dominated by buoyancy or by the fan suction. If the suction speed in the holes is less than 0.0125 m/s, a reverse flow appears at the collector top. When the flow is not uniform, the heat transfer to the rear of the manifold burdens the collector efficiency that depends on the front distribution of suction, which itself depends on the suction fan.

Later, Gunnewiek *et al* [12] improved their model to introduce the wind effect on the flow. As a result, to avoid the reverse flow effect, the minimum suction speed during 5 m/s wind increased from 0.0125 m/s to 0.026 m/s for a wind going towards the building, and 0.039m/s for a wind at 45 degrees angle. The pressure distribution field analysis induced by the wind showed that to prevent reverse flow under wind conditions, it was better not to build the UTC all the way to the top of the building.

Summers *et al* [13, 14] have developed a numerical model with TRNSYS based on heat balances to define UTC operation modes depending on which building the collector is mounted on. The authors were able to perform UTC energy and economic analysis in the state of Wisconsin. They demonstrated that in this state, the UTC economic potential is low. Indeed, for cost reasons, UTC was competitive with electricity. But, not all types of buildings where the UTC could be effective were equipped with electric heating. The UTCs were still recommended for large residential buildings and new buildings.

Dymond and Kutscher [15, 16] have developed a flow model using "fictitious" pipes. This model allowed a "fast" flow calculation without resorting to finite elements/volumes methods that are demanding in computational resources. The approach was to model a pipe network and use the mass balance in the nodes to include the various pressure drops across the collector. Once the flow was known, energy balances were performed, and the flows were calculated in accordance with the fluid properties obtained from the temperatures. Several iterations were made until a converged solution was reached. The example showed the flow velocities, temperatures and the efficiency of a 5mx5m collector with an air outlet at the top. The calculation methodology could enable only one air outlet. This was not considered to be a strong constraint because collectors often have only one exit. They compared the calculation results with thermographic observations of a building and estimated qualitatively that the results were similar. They concluded that the model was able to take into account changes in design parameters of the UTC and that the UTC had the expected behaviour.

Arulanandam *et al* [17] carried-out a numerical study to determine the collector effectiveness. They developed a 3D model representing a quarter of a hole and symmetry planes extrapolated for the whole hole. A total of 216 simulations were made to cover systematically the changes in five parameters established by dimensionless analysis: the Reynolds number in the hole, the plate porosity, the non-dimensional plate thickness, the plate admittance and the radiative Nusselt number. In that study, the plate admittance is defined as the ratio between plate conductivity times plate thickness and air conductivity times the hole diameter. Statistical analysis of these results established a correlation that does not depend on the radiative Nusselt number. The correlation indicates that UTC effectiveness is insensitive to the thermal conductivity of the plate.

Carpenter and Meloche [18] described the calculations performed by the calculation software RETSCREEN and its validation by comparison with the results of the SWIFT program. The calculations of energy savings were based on solar gains, heat recovery through the wall on which the collector is placed and finally the gains due to destratification. Calculations were based on average monthly experimental values. Even if the results from RETSCREEN slightly differ from SWIFT's, they are still considered acceptable for economical feasibility and energy saving calculation.

Gawlik and Kutscher [19] have performed a numerical study validated by tests on the thermal transfer of sinusoidal transpired plates. This study was motivated by the fact that in practice, the plates used for UTC were corrugated while theories are developed for flat plates. This study showed the different flow patterns depending on the conditions and geometries. The authors established a criterion to differentiate attached and separated flows. They established a Nusselt number correlation for each flow type. The same authors [20], later put in place an experiment and a numerical study that confirms that collector conductivity has almost no impact on the collector efficiency.

Frank *et al* [21, 22] have developed a model corresponding to a UTC facility in Kyrgyzstan. The heated air was used to preheat water. In this first stage, they developed a model taking into account standard parameters and application parameters such as unusual convection losses to the environment, the absorption dependence from the incidence angle and building capacity. Their studies showed that once operating parameters are determined, there was no benefit in operation optimization and it was more appropriate to keep these parameters fixed. The solar energy system cost amounted to 0.50 €/kWh, which was well below the market price for oil or gas at the time (2006). Work over component optimization was however yet to be realized.

Leon and Kumar [23] synthetized theoretical analysis, numerical models and experiments to produce their own numerical model to investigate the important parameters in order to operate UTC in the context of drying. Indeed, most studies were dedicated to buildings air preheating or ventilation. The operating conditions for drying have not been studied in depth. Their results showed the key parameters to provide air in a range from 45 to 55°C. These were the absorptivity, the pitch and approach velocity. Emissivity and porosity appear to have a moderate effect. Results produced later by [7] consolidate those conclusions. The authors have produced a number of monograms including several parameters that can be very useful for designers.

Delisle [24] has developed a TRNSYS type to simulate the addition of PV cells on UTC. She adapted Summers [13, 14] and Maurer [25] codes to take into account the wind effect and a corrugated trapezoidal surface. The simulated configurations have PV cells on the upper trapezius or on the entire surface. The simulation results showed that when the air suction is started, the decrease in temperature caused an increase in electricity production. The configuration with PV cell only on the top was more interesting in terms of cost because it avoided placing for PV cells in the shade of the corrugation. After conducting an experiment, the author compared her experimental results with their model [13-15]. The model tended to overestimate the assembly temperature. This could be explained by the fact that the coefficient associated with convective term did not account for wind direction or the trapezoidal shape. Then, two modeling assumptions were not met: the uniformity of the suction and thermal uniformity of the panel. But, when there was no suction, predicted power generation agreed with measurement.

Abulkhair [26] addressed in his thesis the form of trapezoidal corrugated UTC with a numerical model. Manufacturers commonly use this form because it increases the surfaces stiffness. Previous studied forms were mainly flat or sinusoidal surfaces. Its 3-D model predicted successfully separated and attached flows. They happened during low wind (0.5 m/s) and high suction (0.03 and 0.04 m/s). He developed correlations of heat loss in entry regions that are valid for wind speeds of 0.5 to 2 m/s and suction speeds from 0.01 to 0.04 m/s. These correlations were not recognized as high quality by the authors. Efficiency correlations have been developed in the asymptotic region and are valid for suction speeds from 0.01 to 0.04 m/s. It should be noted that efficiency and heat exchange were not expressed as a function of wind velocity. Even if the author argued that it is because they were obtained in the asymptotic region where convective losses are not occurring, most studies demonstrate that an UTC is not wind sensitive above a suction speed of 0.03m/s, for a flat plate.

Into a conference proceedings Moaveni *et al* [27] reported a model using thermal resistance from the building inside to the outside. Comparing the model result and a monitored building in Minneapolis, Minnesota, they found that the percent error is 13.8% of energy savings. The studied building is one of those studied by Tebbe *et al* [28, 29].

In their review, Shukla *et al* [30] compared their model to RETSCREEN and Swift evaluation. They showed that SWIFT over estimates the total heat delivered due to an abnormally large amount of heat savings during summer. They also compared the TRNSYS results to experimental fittings and showed good agreement for suction speed over 0.02 m/s. Below this value, TRNSYS over estimates measurements.

Numerical studies showed that even if UTCs are more effective and economic against other solar system, this advantage doesn't prove always right against traditional heating system. Cases by case analysis are needed. Conductivity doesn't seem to be important in the UTC effectiveness. Heat exchange is strongly geometry dependent and a minimum suction speed (0.026 m/s to 0.036 m/s depending of the wind direction) is required in order to the UTC to be unaffected by the wind. Since most studies were made with flat plate geometry, recent models were developed to take into account sinusoidal and trapezoidal shape. The latter is the most used in the industry but simulation results are not yet conclusive. Recent studies are taking interest in the energy stocked into the rear wall.

3. Experiments

In his thesis and in one article, Kutscher [8, 31] presented an experiment that has shown that the suction rate, the hole pitch, the hole diameter and wind speed were key factors in determining the heat transfer. The thickness of the plate and its orientation have little importance. The results without wind and with three wind speeds helped to develop a correlation to predict heat transfer effectiveness. A pressure drop correlation was also developed so that a designer can select the fan. Finally, measurements with wind have been taken to show that wind losses are negligible. Van Decker *et al* [32] raised the experimental validity ranges used by [8, 31], completed the effectiveness correlation and added thickness and conductivity effects. Later, since the model from [32] was inconsistent for the no wind condition, the authors [33, 34] sought to include no wind conditions into their correlations. This led them to reconsider the correlations they had proposed before. The new ones give results that are accurate from no wind conditions as for windy ones.

Golneshan and Hollands [35, 36] conducted an experimental study on plates with slots and have established a correlation to determine the collector efficiency according to a dimensionless flow parameter factor that in turn depends on the surface air speed, the collector length, the air viscosity, the air velocity and the plate porosity. This dimensionless parameter can be view as the product of the Reynolds number and a velocity ratio (suction to wind velocity).

Deans *et al* [37] have set up an assembly with a corrugated panel. Their results showed that the most influential elements onto the collector performance are irradiance, wind and air flow passing through the collector. They also showed that improving the heat exchange could be done from the rear panel by increasing the airflow thus reducing the temperature of outlet air. Later, they [38] continued to work on this installation and performed numerical studies. They showed that much of the heat transfer took place behind the collector near by the top of it. At the top, the dominating heat transfer mechanism is the mix of the incoming air and the one already in the collector.

Badache [39] used the experimental design method to design an UTC experiment to determine the parameters affecting the performances. The control parameters used were the perforations diameter, the fan outlet flow, the incident radiation and the absorber coating. The ambient temperature was the noise parameter and response parameters were the outlet air temperature and absorber temperature. Data analysis showed that the three main parameters are the absorber coating (absorptivity and emissivity), radiation and fan flow.

Gao *et al* [40] have set up an experiment exposing a 2.5m^2 UTC to weather conditions for four days. From the operating conditions, they calculated the efficiency that varied from 61% to 78%. They concluded that the temperature rise diminishes and efficiency rises with higher suction rate. That is coherent with previous theoretical [2] conclusions.

Moaveni *et al* [41] took interest into the energy stored into the wall when a UTC is in place as well as its effect onto the wall temperature. For the building they monitored in Minneapolis, they found out that the wall outside temperature at night when having an UTC was about 8°C higher than without. Additional energy stored into the wall varies during the monitored time from 2.6 Gj/m^3 to18.1 Gj/m^3. The authors conclude that the amount of energy stored into the wall is significant and should be accounted in the collector efficiency calculation.

In their performance study, Chan *et al* [42] focused their interest on the contribution of heat exchanges behind the plenum. They showed that this heat exchange contributes for 50% of the total air temperature rise under common use conditions. This differ from the results of [34] which showed that the back of the plate have a contribution of the order of 10%. The authors suggested that this difference could be due to the size of the test bench. Van Decker [34] workbench was four times smaller and other effects like significant buoyancy could not occur.

From the late 1990s, experiments started to test the use of photovoltaic (PV) cell mounted onto the UTCs. The argument is that irradiated PV cells produce electricity but are also heated by solar radiation. By placing PV cells on an UTC, the air cools the PV cells and allows better performances (performance of PV cells decreases with increasing temperature).

Hollick [43] presented the results of tests where PV cells were mounted on an UTC. Experiments showed actual gains in PV cells performances, but these were minimal.

Naveed *et al* [44] looked at the effect of mounting solar cells on UTC. They followed the cells power generation and temperature. In their apparatus, PV cells showed a reduction of 3 to 9°C in surface temperature. This experience was used to validate a numerical model. With this model, the authors calculated that to produce 3 kW by PV in the same operating conditions, a PV panel mounted on a UTC would require three less 75 W modules. The analysis shows that the economical payback of the PV panel reduces from 23 to 15 years when used with an UTC.

To test her TRNSYS model, Delisle [24] made a set-up where she installed a PV cell on a 2.8m^2 UTC. Trends were those set out: the greater the suction, the more the temperature of PV cells and heat collector drops. For cons, the temperature increase and thermal efficiency of the collector were less than expected. This could be attributed to the non-uniform suction that failed to extract maximum heat from the panel and losses by wind due to the panel small size.

Athienitis *et al* [45] had photovoltaic panels mounted on an UTC. The assembly comprised two panels exposed to the same external conditions. The first was a conventional UTC used as a reference, the second, designed to maximize absorption of solar energy and heat, was an UTC covered with 70% of PV cells. Although the PV mounting showed a heat balance below that of the conventional UTC, if one considers the electrical efficiency and that electricity can be converted to four times more heat (assuming it is used by a heat pump with a coefficient of performance of at least 4 in the temperature range considered), the overall UTC/PV panel thermal efficiency was 7% to 17% greater than the conventional UTC panel.

Experimental studies permitted to develop effectiveness correlation for wind and no wind conditions. Wind speed, suction speed, radiation, are the most cited parameters that influences the results. Heat exchange behind the panel still needs studies in order to improve the system. Very few experiments take the corrugated shape into account. Adding PV over UTC is recent development. The cooling effect of the PV by the air flowing into the UTC is real but the gains are not easily exploitable. An original solution is to add another component like a heat pump to improve the thermal efficiency. Contrary to classical UTC studies, almost all PV-UTC studies use a corrugated/trapezoidal shape panel.

Barker & Kiatreungwattana [46] conducted a series of laboratory tests to characterize the pressure drop across the absorber as a function of air flow rate, density, and viscosity for the six commercially-available absorber configurations; three porosities in aluminum and three in steel. The absorber manufacturer ATAS INTERNATIONAL, INC. of Allentown provided samples. Before this lab experiment, field test were conducted on roll-punched-slit absorbers (Barker & Hancock[47]). These data were aligned with models developed for round-hole configurations. However, only one system had a pressure drop above about 7 Pa. The tests were conducted on 0.176 m2 samples under controlled laboratory conditions. Average pressure drops across the absorber over a wide range of air flow rates were measured along with the temperature, relative humidity, and total pressure of the ambient air being drawn into the absorber. Recommended suction velocity were chosen to achieve a 25 Pa pressure drop. For aluminium panels, these varied from 0.041 m/s to 0.060 m/s in function of the porosity; for steel panel, these velocities were between 0.035 m/s to 0.056 m/s

4. Implementations studies

Carpenter and Kokko [48] followed three facilities with three solar technologies. The first was a set of transparent plastic plates 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 an UTC. The results and their extrapolation showed that the UTC was the most efficient system.

Kokko and Marshall [49] analyzed the functioning of a factory where an UTC with a "canopy" was installed. They showed that this design increased the efficiency by 16%. At high air flow (90 m^3/h per m^2 of collector), the reference UTC showed 44% efficiency, the one with a canopy showed 50% with high wind and 70% with no wind. Placing the opening of the air bypass onto the canopy helped avoiding the suction effects at the fan opening. Then, the airflows were more evenly distributed through the wall compared to UTC without a canopy. Finally, reducing the delivered air temperature by increasing the airflow could increase the collector performance, solar heat delivered and destratification.

Hollick [50] demonstrated the results of various facilities in Ontario, Canada and in Germany on a large scale implementation. He showed 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 [51] described two implementations. The first one was at Windsor (Canada), where the height of the UTC was the highest known at the time. This height induced a strong chimney effect and return on investment was estimated at 6 years. The second implementation was at an industrial building of Canadair in Montreal and had an immediate return on investment (ROI) because the work had cost the same price as the facades to be refurbished, the energy and economic gains were 8.3 GWh and $CAN180,000 per year, respectively.

Mier [52] has set up a system in order to measure winds, UTC temperatures and in its pipes to see wind effect on the collector efficiency. Despite the technical difficulties associated with measuring devices and the collector installation, the author was able to conclude that the effectiveness and efficiency were affected by the wind. Performance tended to increase when the wind coming from above by the building created a recirculation/stagnation zone. This recirculation was recapturing the convection losses. The collector surrounding had an impact on the local wind. For example, the heated gravel in front of the collector created draft by natural convection. Also, a wind coming to the collector face increased effectiveness while a side wind reduced it. In addition, the effectiveness decreased with increasing turbulence around the collector. Fleck *et al* [53] continued those studies and found out that contrary to Kutscher [8] theories, maximum efficiency was not reached with zero wind speeds but with average wind between 1 and 2 m/s. The authors proposed no explanations for this phenomenon. This second study confirms that the turbulence associated with wind reduced collector effectiveness. The authors pointed out that unlike the ideal case of the developed theories, the materials used are corrugated which was an additional source of turbulence. At the time of article writing, the authors were still looking for a correlation between wind direction and its effect on the system. Kutscher *et al* [54] reviewed this late article to show that operating conditions of 0.01 m/s described by [53] were not those which allowed to say that UTC are not wind sensitive (suction speed at least 0.02 m/s, pressure drop across the wall of at least 25Pa, flow uniformity). They put their experiments in perspective with those of [53], stating that the result of the later only apply to the reduced flow condition of their design.

Maurer [25] kept track of a solar wall installed in North Carolina. As the heating season is short in this area, there were questions on such systems economic viability. The records showed that there were design and operation problems that kept it from running at full capacity. Although the collector supplied hot air, there was still stratification in the building. The TRNSYS model has shown the need to make changes in the program and, for a specific results, this simulation should be coupled with a CFD analysis. Second, the study showed that during the hot season, the collector heated the wall where the UTC was mounted. This effect will be more due to radiation than by convection in the plenum. Finally, the system was economically viable; the payback was found to be from 5 to 7.4 years depending where it was installed and on the inclusion of taxes credit. This result cannot be generalized and a case-by-case analysis is needed.

Cordeau and Barrington [55] analyzed the collectors' efficiency installed on two barns. Each building floor was equipped on the southeast front with 1% perforated collectors. They measured the incident radiation with an uncertainty of 7% and have validated a method for theoretical calculations using a ground albedo of 0.2 in the summer and between 0.3 and 0.6 in winter, depending on the snow cover. Apart from irradiation, wind was the factor having the greatest influence on the efficiency, which went from 63% for a 2m/s wind of to 25% for 7m/s wind. During winter, the savings were 14.8 \$CAN/m^2 which represents a 4.7% annual ROI based on the initial capital cost.

After describing its UTC and UTC/PV efficiency comparison experiment, Athienitis et al [45] briefly presented this kind of system on the top of a Montreal building. In conference proceedings, Bambara et al [56], exposed more thoroughly this implementation, describing all the systems design and operating mode. The system can provide one fifth of the ventilation volume and raise the total entrance air temperature by 3.5°C. A global efficiency on the order of 50% is reached.

Into a proceeding and a report Tebbe *et al* [28, 29] described the analysis of UTC implementations under Minnesota climate. They tried to compare six implementations but only three systems went through the analysis process. They concluded that UTCs were suitable for the Minneapolis-St. Paul heating season. Observed behavior matched with the one described in the literature as temperature increases form 14 to 25°C, exit temperature rises and efficiency decreases as approach velocity is reduced. Since typical insulation in the region is high, the contribution from the wall heat recovery is lower than in other locations. The average efficiency varies form 45 to 55%.

Large scale implementations showed that UTC is often superior to other solar air heating systems. On top of theoretical and experimental aspect, design, like canopy, and big scale implementation reduce the impact of certain phenomena like the side effect or amplify contributing effects like the stack effect. Even after numerous implementations, wind sensitivity seems to be questionable, but the design and operating conditions of this experience needs to be reviewed. Other considerations such as the duration of heating seasons is also to be considered and a case-by-case analysis is required.

Kozubal et al [57] studied the installation of 744 m^2 of UTC at a Wal-Mart, in Aurora, Colorado. The measured efficiency was established at 8-11% during January and February 2007. The low collection efficiency is largely due to the oversized absorber and to the multizone control strategy that limits the amount of air pulled through the collector. Analysis shows that more than 50% of the incident solar energy could be delivered with proper control strategy changes.

Brown [58] evaluated the use of solar air heating at U.S. Air Force installations based on an UTC (it this case Solarwall®). He sought to determine if UTC systems are an economically and environmentally viable technology, which Air Force energy managers should include in their portfolio of alternative energy options. This research question was answered through the use of case studies and life cycle cost analysis. Case studies were performed at various U.S. military installations, which have already utilized UTC systems to provide a consolidated source of lessons learned. The quantitative results of this evaluation determined that the Air Force could realize significant economic and environmental benefits from the use of UTC technology.

5. Applications

Pesaran and Wipke [59] studied the use of UTC in a cycle of air cooling/drying. The air is dehumidified and cooled before going to the building. The air pumped out of the building serves to pre-cool the incoming air. It is later re-heated to regenerate the rotary desiccant dehumidifier material. The UTC serves as a heat source for regeneration. Their calculation compared the use of a glass collector and UTC. They showed that the system using UTC had a thermal coefficient of performance 50% smaller than the on using a glass collector. The efficiency of the UTC was 20% larger than a conventional collector for a regeneration temperature of 70°C. Although UTC required a larger area than a glass collector, its lower cost made it an attractive option. However, a natural gas installation was still cheaper. Practical considerations may limit the usefulness of this configuration for cooling desiccant systems.

Summer *et al* [14] showed that in the state of Wisconsin, the economic potential of UTC is low. Indeed, for price reasons, UTC was competitive with electricity. But, all types of buildings where the UTC could be effective were not equipped with electric heating. The UTC was still recommended for large residential buildings and for new buildings.

In its report of IEA 14th task, Brunger [60] described the follow-up on several large UTC installations and software design tools. In the second part of the report, he presented with more details the results of research conducted at National Renewable Energy Laboratory (USA) and at Solar Thermal Research Laboratory (Canada). Main results show the impact of evenly distributed suction with a canopy, the effect of pre-heated air for combustion, the wind impact on UTC. The same kind of information can be found in the « technological alert » [61], [62]. Those were more oriented for federal building managers in the USA for UTC uses.

Hollick [63] presented the use of UTC for agricultural production drying. He showed that UTC could complement existing practices using fossil fuels. The main application described for drying of sesame seed shall have a 2-year ROI.

After having presented a UTC model adapted for tropical region crop drying, Leon [23], [64], [65] continued to develop drying applications adding solar technology to a biomass burner and a rock bed. The system not comprising conventional burner was able to sustain 90% of heating charges during days and nights of operation.

Gao [66] described the UTC heating potential in five northern Chinese cities, comparing heat gains for a same building with the same UTC installation. Authors claim heat gains going from 16.5 to 23% and 6.4 to 10.7 years for ROI. Using RETCREEN, Gong *et al* [67] widen the number of cities to fifteen. Their analysis conclude that in order to make UTCs profitable for half the site, the energy would have to be increase by 95% or the flat plate price should falls 50%.

Hassanain [68] studied three techniques for drying medicinal plants: direct solar exposure, into a house for which the roof was heated by the sun and finally by a perforated solar collector. The geometry of the perforated collector varied greatly from that of UTCs studied previously. It had a plate inclined at 45 degrees (to compensate for the latitude of the place of study, in Egypt) and facing south. The plants to be dried were placed directly behind the perforated plate and the fan was placed behind the plants. The study showed that direct exposure provides greater reduction in humidity, the solar collector allowed the production of more rosemary and marjoram oil, and finally that the oils obtained from plants dried in the solar collector had better score in terms of color, smell and taste in the sensation tests.

Application studies show that design is key to ensure proper heat collection. In competition with other solar heating technics, UTC is more profitable but against fossil fuel. This indeed depends on the fuel prices. For crop and agricultural product drying, UTC is efficient, yielding under three years ROI and in some applications ensures 90% of energy needed for drying.

6. Conclusion

A detailed review of the UTC technology was carried out covering studies from the late 80s until now. This review was divided into theoretical, numerical, and experimental studies as well as implementations studies and applications. In several cases, of course, these studies were discussed into several sections as they involve experimental and numerical work, for instance.

UTC is a technology for which several basic physics parameters were found to determine the global performance of the units in laboratory conditions. The current investigation can then provide overall guidelines for the designer. The following parameters could be recommended: minimum suctions speed (0.04m/s in the hole for non-wind sensitive UTC), orientation (south in the north hemisphere, of course), radiative absorption (the higher the better), low emissivity for long wavelength specifically for external surface temperature above 40°C, wind condition (under 7m/s), and minimum aspiration pressure (25 Pa).

However, it was found that in most cases, ideal geometries were investigated (flat plates, circular perforations, ideal plenums involving no obstacles, etc). Hence, some other effects such as corrugated plates, hole shapes, flow paths, actual pressure drops, slope etc., still need further studies.

On the other hand, real implementation studies showed that for parameters found to have little or no influence on efficiency in laboratories, results are or may be very different in the context of an *in-situ* large scale UTC. For large implementations, customized design is always a key factor to propose a well-functioning UTC and threshold values for some parameters that ensure proper efficiency in laboratories may not be appropriate for all cases.

Finally, operating parameters need more studies to optimize the UTC usage: the design will be different for building heating than for crop drying or solar cooling. Moreover, relatively new applications, like the combined UTC-PV system, seem to be the new trend to the UTC evolution. More research should be carried-out in this field.

After studies mostly driven from an interest in North America in the 80’s and applications limited to building heating, UTC are now more and more adopted throughout the world for many different applications. As a result, there is still a lot of optimization required in order to reflect the implementation in many aspects of heat recovery use.

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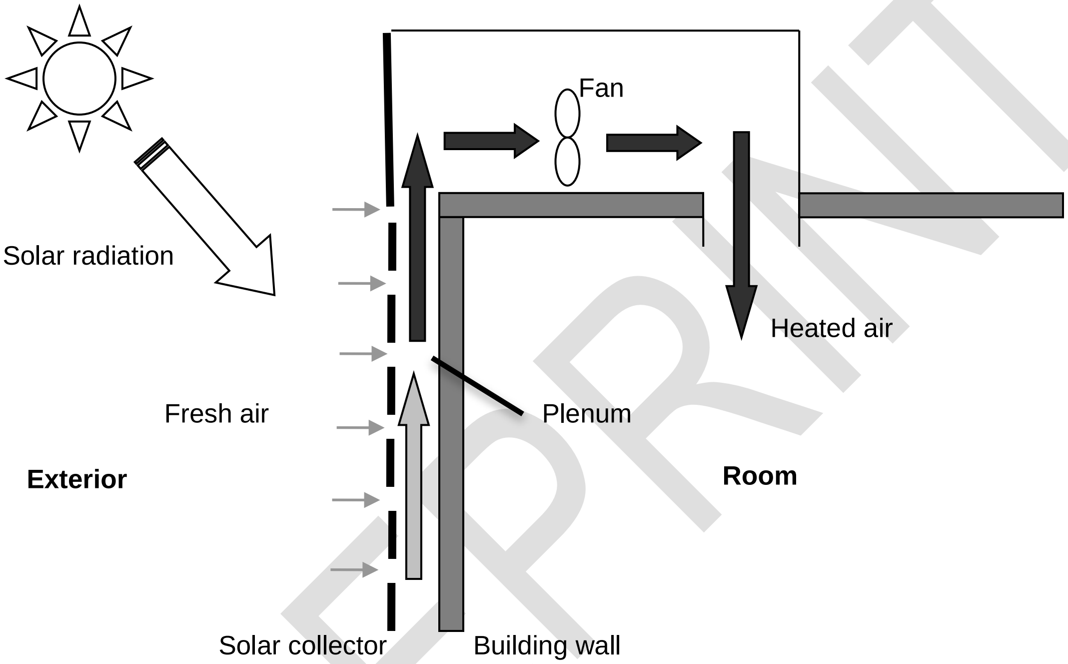

Figure 2