ST-31

SESCI 2004 Conference
University of Waterloo
Waterloo, Ontario, Canada
August 21st–25th, 2004

INTEGRAL STAGNATION TEMPERATURE CONTROL FOR SOLAR COLLECTORS

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ABSTRACT

Solar collectors to reach very high temperatures, particularly during power failures or periods when there is minimal energy demand. Under these conditions, solar collectors may reach "stagnation" temperatures exceeding 170°C. If exposed to these high temperatures, the heat transfer fluid may rapidly degrade or even boil. In addition, excessive pressures may occur in the solar collector heat-transfer loop during stagnation conditions. High solar collector temperatures can also produce scalding temperatures in the hot water storage -- a potentially danger for residents. Recognizing the harmful effects of stagnation, a mechanism for limiting the temperature of solar collectors was developed. During the course of this study, a detailed heat transfer and thermal analysis was conducted to arrive at a suitable design. Based on this analysis, a prototype collector was constructed and tested under typical stagnation conditions. The results of these tests confirmed the operation of an integral temperature-limiting configuration. An important feature of the implemented design is that it operates "passively", requiring no user intervention or external power source. As well, the operation of the solar collector is not affected during normal (i.e., non-stagnation) conditions. This paper describes the analysis, design and operation of solar collectors equipped with temperature control features.

INTRODUCTION

Background: with all solar water heating systems there is the potential for the solar collectors to reach very high temperatures, particularly during power failures or periods when there is minimal hot water consumption. Under these conditions, the solar collectors may reach "stagnation" temperatures exceeding 170°C. If exposed to these high temperatures, the heat transfer fluid may rapidly degrade and excessive pressures may be produced in the solar collector heat transfer loop.

The problem is particularly acute, in climates where there is a potential for freezing temperatures during part of the year. Solar systems designed for these climates typically use an anti-freeze solution to transport heat from the solar collectors to a load. The most common anti-freeze fluids used in solar systems are propylene-glycol/water mixtures that typically subject to deterioration at elevated temperatures, i.e., greater than approximately 120°C. Under these conditions the heat transfer fluid may become corrosive, resulting in accelerated fouling and corrosion of the solar system components.

In addition to these durability issues, high solar collector temperatures may also result in scalding temperatures in the hot water storage. To avoid this potentially harmful situation, it is common practice to shut down the circulation of heat transfer fluid through the solar collectors (by shutting down the circulation pump) when the thermal storage reaches a high temperature. While this reduces the potential for scalding, it only accelerates the degradation of the heat transfer fluid in the anti-freeze circulation loop and the solar collectors.

To eliminate the harmful and damaging effects of stagnation, temperature-control should be addressed in the solar collectors. In principle, there are two ways to control collector stagnation temperature: reduce solar energy input into the collector or remove excess heat from the collector. To prevent overheating, the dissipation of heat from the collector through natural convection is preferable, both technically and economically. As such, this paper describes solar collectors with natural cooling, i.e., "self-limiting", features. This new design incorporates an Integral Stagnation Temperature Control[1], (ISTC). To develop this concept, a theoretical and experimental study was undertaken.

Stagnation Conditions: for the purpose of this paper, "stagnation' conditions are considered to be any situation under which the solar collector can not adequately reject absorbed solar heat to its primary heat transfer fluid, thereby resulting in the solar collector and/or its components (including the heat-transfer fluid contained within its flow passages) to increase in temperature above a desired maximum level. Examples of this condition include sunshine periods when the flow of heat transfer fluid is interrupted due to: power failures; component failures, (e.g., circulating pump); system servicing or repair; and pump-controller intervention due to energy storage capacity limitations, etc.

The magnitude of the temperature reached during stagnation conditions is dependent on climatic conditions and solar collector design and orientation. Many solar collectors are mounted directly on the roofs of buildings, typically at low tilt angles (e.g., approximately 18^o to the horizontal). These systems are particularly susceptible to high stagnation temperatures because of the coincidence of high summer solar radiation levels on the solar collector and high ambient air temperatures. For example, hourly solar radiation intensity and ambient temperatures of 1000W/m² and 30°C, respectively, may occur during the April-October period in many locations in the Northern Hemisphere (e.g., Toronto, as shown in Fig. 1). Therefore, for this study, a solar radiation level of 1000 W/m² coincident with ambient temperature of 30°C was considered the design condition for stagnation temperature control.

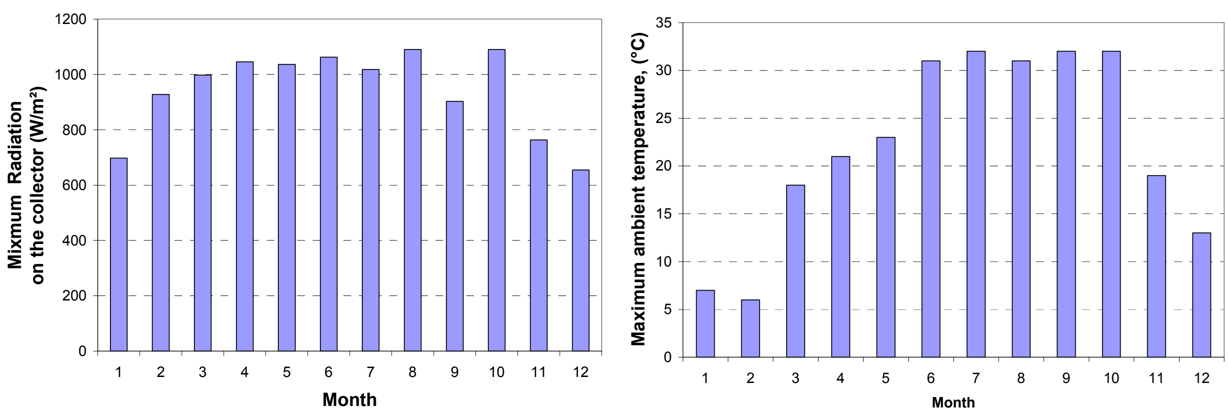

Figure 1: The maximum monthly solar radiation and air-temperature in the Toronto area.

STAGNATION TEMPERATURE CONTROL

The thermal performance of conventional solar collectors is well established, (Duffie and Beckman, 1991). Under normal operating conditions, the rate of energy delivery to the load by a solar collector, Q_{del}, is determined by the difference between the rate at which solar energy is absorbed in the solar collector, Q_{abs}, and the rate of heat loss from the solar collector housing, Q_{loss}, i.e.,

$$Q_{del} = Q_{abs} - Q_{loss} \quad (1)$$

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[1] Patent Pending

where: Q_{abs} is determined by the product of the solar collector area, A_c , the transmittance (τ) of the glass cover and the absorptance (α) of absorber plate and solar intensity G, i.e.,

$$Q_{abs} = A_c\,(\tau\,\alpha)\,G \tag{2}$$

and Q_{loss} is given by the product of the total collector heat-loss coefficient (U_L) and the difference in temperature between the solar collector absorber plate and the surrounding air temperature, i.e.,

$$Q_{loss} = A_c\,U_L\,(T_p - T_a) \tag{3}$$

Under stagnation conditions, no heat is delivered to the load and thus $Q_{del} = 0$. As such, to control collector temperatures under "stagnation temperature" conditions, a solar collector must be able to dissipate all the absorbed energy. In effect, the temperature of the solar collector absorber will increase until $Q_{loss} = Q_{abs}$ or,

$$U_L\,(T_p - T_a) = (\tau\,\alpha)\,G \tag{4}$$

Using this expression, we can estimate the temperature of the absorber during stagnation by solving for T_p, i.e.,

$$T_p = T_a + (\tau\,\alpha)\,G/\,U_L \tag{5}$$

For typical collector designs, $(\tau\alpha)$ = 0.8 and U_L = 5.5. Therefore, for an incident sun intensity of 1000 W/m^2 and T_a=30^{o}C, the stagnation temperature of the absorber, T_p, would be 175^{o}C. Similarly, to limit the absorber temperature to less than 120°C, the total collector heat loss (U_L) would have to increase to 8.9 W/m^2 °C.

Heat loss normally occurs from the top, sides and bottom of the solar collector housing. In a traditional flat-plate collector design, heat loss from the top of the absorber plate to the cover glass (and surroundings) occurs by convection and re-radiation. Heat loss from the sides and bottom is dependent on the thermal resistance of the collector housing, (which is usually insulated). Current designs are typically insulated such that the thermal resistance level through the back and sides of the collector housing are approximately 1.5 W/m^2 °C.

The top heat loss from a collector depends on the properties of the glass, the absorber coating and the thermal resistance of the air-layer between the absorber and the glass. For a typical collector design, the top heat loss is a function of the absorber-plate temperature and approaches 4 W/m^2 °C for an absorber temperature of 120°C. Therefore, the goal of integral stagnation control design is to enhance heat loss from the collector, from a typical value of 5.5 W/m^2 °C, to 8.9 W/m^2 °C whenever the absorber temperature approaches (and exceeds) 120°C. At lower temperatures, the heat loss from the collector should not be affected, thereby assuring that it is minimized during normal operation.

Integral Stagnation Temperature Control, (ISTC): after extensive analysis and laboratory testing (Qin and Harrison, 2003), it was concluded that the most practical and reliable means of increasing the heat-loss characteristics of a solar collector during stagnation was to incorporate cooling a channel under the absorber plate. This channel would be used to introduce ambient air between the absorber plate and the back insulation thereby allowing the natural convection cooling of the collector absorber plate, Fig. 2. These channels must dissipate up to 400 W/m^2 if the stagnation temperature is to be limited under extreme conditions.

For the proposed design, a thermally-actuated valve at the upper periphery of the collector opens under stagnation conditions allowing hot air to exhaust from the top of the collector and cool ambient air to enter at the bottom of the collector. This air is heated in the venting-channel behind the collector absorber, thereby removing excess heat from the back of the absorber plate. The movement of the air is driven passively by a temperature-induced density gradient that exists in the air in the venting-channel. At collector temperatures below a prescribed control point, the thermally actuated valve closes, restricting the circulation of air through the solar collector. Under these conditions, the air in the venting channel is thermally stratified and remains stationary, acting as an insulating layer to heat loss from the back of the solar collector.

The design and geometry of the integral air-channel must be specified to ensure that there is sufficient airflow to adequately cool the absorber under stagnation conditions and to ensure that adequate heat transfer rates exist in the channel. The dimensions and tilt angle of the channels affect the rate of natural convection airflow, and consequently, these affect the rate of heat removal from the absorber plate. A large channel cross section will increase heat removal but will also increase the overall dimensions of the solar collector, while; a smaller channel will result in higher stagnation temperatures. Based on computer modeling and laboratory testing, a cooling channel of between 15 and 20 mm depth was found to be adequate if the interior of the channel was coated with a high emissivity coating. The high emissivity on the channel surface enhances the radiative heat transfer from the bottom surface of the absorber (that forms the channel roof) to the other walls of the channel.

Cooling of the back of the absorber rather than simply the collector housing or the front of the absorber is used to eliminate the potential of dirt and dust being drawn into the collector and deposited on the optical surfaces of the solar collector, e.g., the solar collector's optical absorber coating or the interior of the cover glass. These latter conditions would degrade solar collector performance over time and increase maintenance requirements.

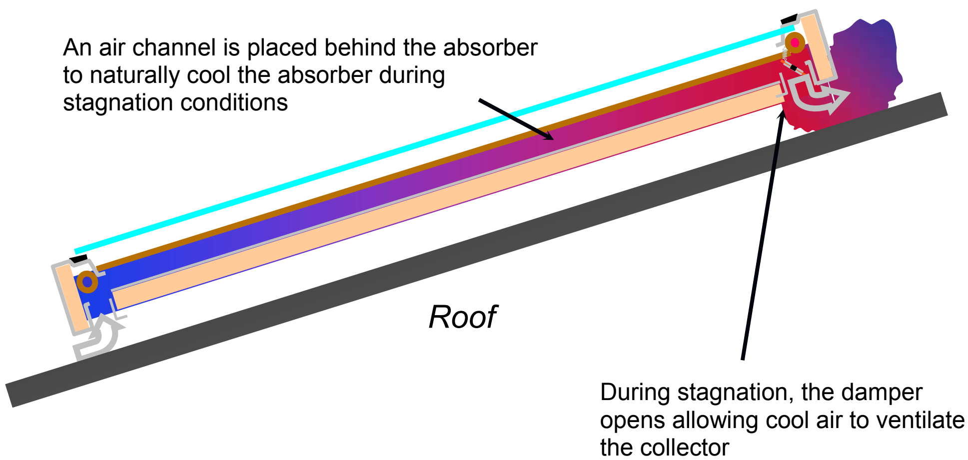

Figure 2: Conceptual design of a solar collector with integral stagnation temperature control.

Thermally Actuated Control Valve: while analysis and testing indicated that it was possible to reject adequate heat during stagnation to limit the solar collector temperature to suitable levels, a criterion of the integral stagnation control was that it not degrade solar collector performance during periods of normal operation. To meet this objective, a thermally activated valve assembly was placed at the outlet of the channel. This valve was designed to open under stagnation conditions and to remain closed at all other times. When the valve was closed the air was trapped in the channel. To be truly functional, the valve operation must be independent of any power source and operate under all conditions, e.g., power failures, etc. For this reason, thermally actuated valves are ideally suited to this application, and can be tuned or fabricated to open at any desired temperature.

A number of thermal actuators could be used to control the operation of the upper valve assembly, including gas-charged pistons, wax filled actuators, bimetallic springs and shape memory alloys, etc. For the purpose of testing, a sample valve assembly was constructed based on the use of shape memory alloy (SMA) springs, (Otsuka and Wayman, 1998). The SMA springs could be fabricated to exert a force at a preset temperature, thereby opening the valve assembly, allowing the natural convection of air through the cooling channel located below the absorber plate of the solar collector.

Through this method, a solar collector with two distinctly different heat loss characteristics could be obtained. In effect, at temperatures below a predetermined limit, the collector exhibited the thermal properties of a high performance solar collector, and at temperatures above this value, the heat loss rate from the collector was dramatically increased, capping the temperatures in the collector.

EXPERIMENTAL EVALUATION OF A PROTOTYPE COLLECTOR WITH ISTC

To verify the functional performance of the ISTC solar collector concept and the operation of the Integral Stagnation Temperature Control (ISTC) feature, a prototype solar collector was designed and constructed for experimental testing under real environmental conditions Fig. 3.

Figure 3: Prototype solar collector with the Integral Stagnation Temperature Control (ISTC) feature constructed for this study.

The collector fabricated for this study incorporated a parallel riser design with upper and lower header pipes. Prefabricated tube and sheet absorber strips were folded to form the integral air channel located below the absorber. The upper surface of the absorber was pre-coated with a “black chrome” selective absorber coating and the back surface of the absorber was painted with high emissivity black paint. The details of the prototype collector and control valve are shown in Figs. 4 and 5.

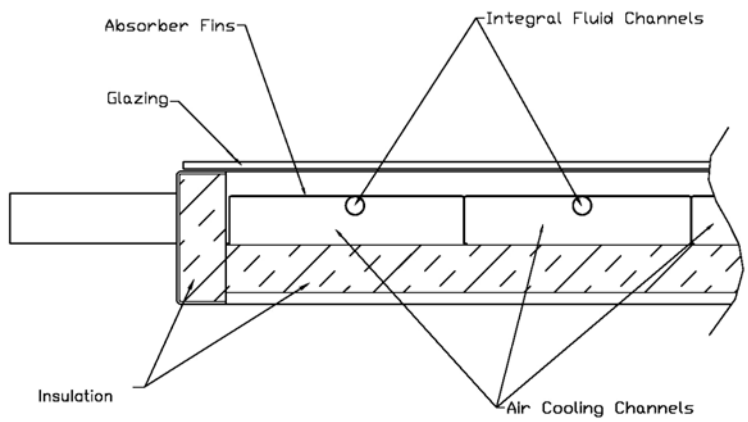

Figure 4: Cross section schematic of the solar collector with integral cooling channels placed below the solar collector absorber plate.

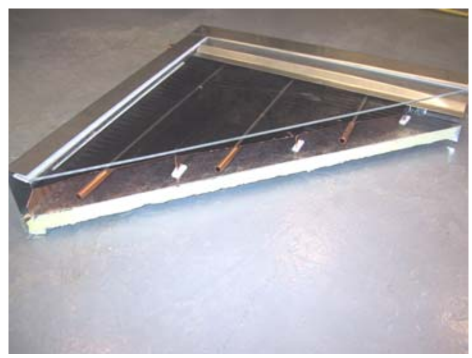

Figure 5: LHS: rear view of the ISTC solar collector showing thermally activated valve (i.e., a vent damper) on the top rear of the collector. RHS: Cut-away section of the solar collector.

TEST RESULTS

Tests were performed on prototype ISTC collector during May-June of 2002, at the Solar Calorimetry Laboratory at Queen's University in Kingston, Ontario. Figure 6 shows a photo of the ISTC collector positioned next to a reference collector used to verify the operation of the stagnation control. The reference collector consisted of an absorber strip that was well insulated and therefore indicated the unrestricted stagnation temperature that would occur in a typical solar collector under the test conditions. Both collectors were oriented at an 18° tilt to the horizontal and were faced due south for the stagnation tests. To simulate an extreme stagnation condition, both collectors were tested "dry", with no circulation of heat transfer fluid.

Both the reference collector and the ISTC collector were instrumented with thermocouple temperature sensors. Temperatures on the ISTC collector's absorber and the back of the venting channel were measured. Measuring points were located on the collector bottom, close to the inlet, the middle of the collector, and top of the collector close to the temperature-controlled valve. During the test period, the ambient air-temperature, temperatures in the collector and solar radiation on collector surface were measured. A computer-based data acquisition system was used to collect the test data. All measurements were recorded as mean quantities over 5 minute periods.

Figure 6: Outdoor test setup used to evaluate the ISTC solar collector.

Stagnation temperatures in both collectors were monitored over extended period. Figures 7 and 8 show the maximum temperatures in both collectors and the corresponding solar radiation and ambient temperatures for two clear-day tests (25th May and 7th June). Both ISTC and reference collector's temperatures rose as the solar radiation level increased. The results show that the maximum temperature in the ISTC collector was slightly higher than that in the reference collector at temperatures below 100°C. As the solar radiation level increased beyond this point, the temperature of the ISTC collector was observed to increase at a slower rate than the reference and to stabilize at around 122°C. The reference collector reached a temperature of 155°C during the corresponding period. The operation of the control valve was verified by visual inspection during this time. Later in the day, as the intensity of the sun dropped, the valve was observed to close and the discrepancy between the collectors' temperatures disappeared. These results indicate that the heat loss from both collectors was identical below 90°C and that the heat loss from the ISTC collector was significantly increased above 100°C. The heat loss coefficient was calculated for both collectors. It was found that the heat loss ranged between 6.1 - 6.3 W/m² °C for the reference collector and 6.1 - 9.6 W/m² °C for the ISTC collector.

Temperatures were recorded for both collectors over a 5-day period from June 5th – 9th and are shown in Fig. 9. These results verify the operation of the stagnation control features of the ISTC collector and demonstrate that high temperatures in the collector absorber may be limited by this method.

In addition to the comparative tests described above, the maximum stagnation temperature of the ISTC collector was determined for the case with the integral stagnation control disabled. This was done for two reasons, i.e., to confirm the heat loss characteristics of the ISTC collector without the stagnation control, and to quantify the maximum stagnation temperatures under this condition. For this test, the exit of cooling channel was sealed. Results obtained indicate that the temperature reached by the disabled ISTC collector was slightly higher than that in the reference collector throughout the day. With a solar radiation intensity of 1150 W/m^2 and an ambient temperature of 25°C, the maximum stagnation temperature was 170°C in ISTC collector and 160°C in the reference collector. This result indicates that the closed ISTC collector had a slightly lower heat loss characteristic than the reference collector under normal operating conditions further illustrating the benefit of the integral stagnation control.

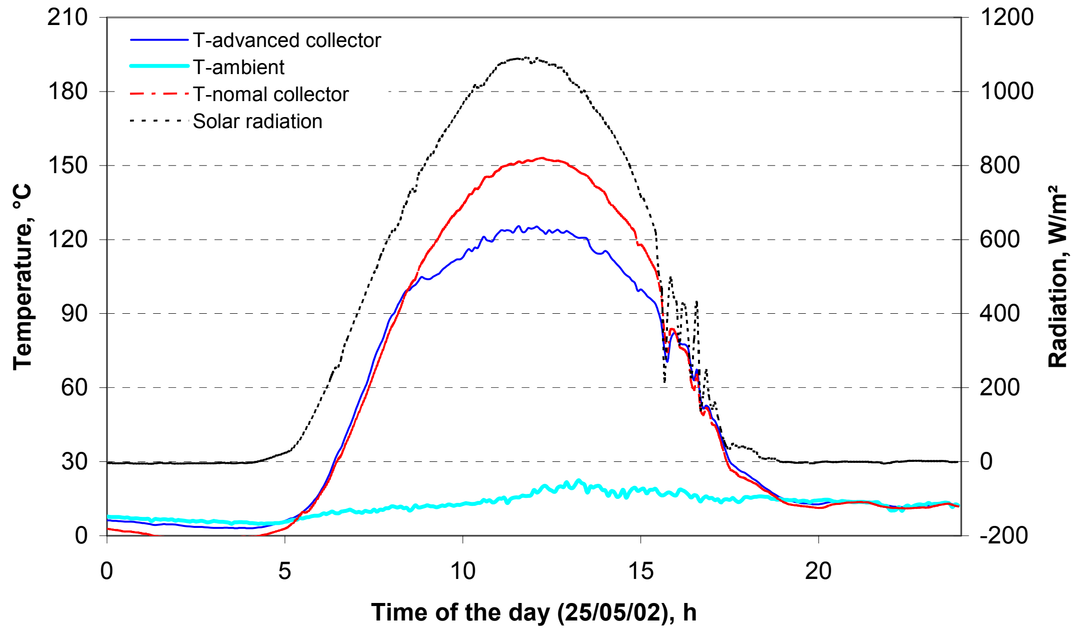

Figure 7: Recorded temperatures and solar radiation intensity on May 25, 2002, (temperatures recorded for the ISTC collector are designated "T-advanced Collector").

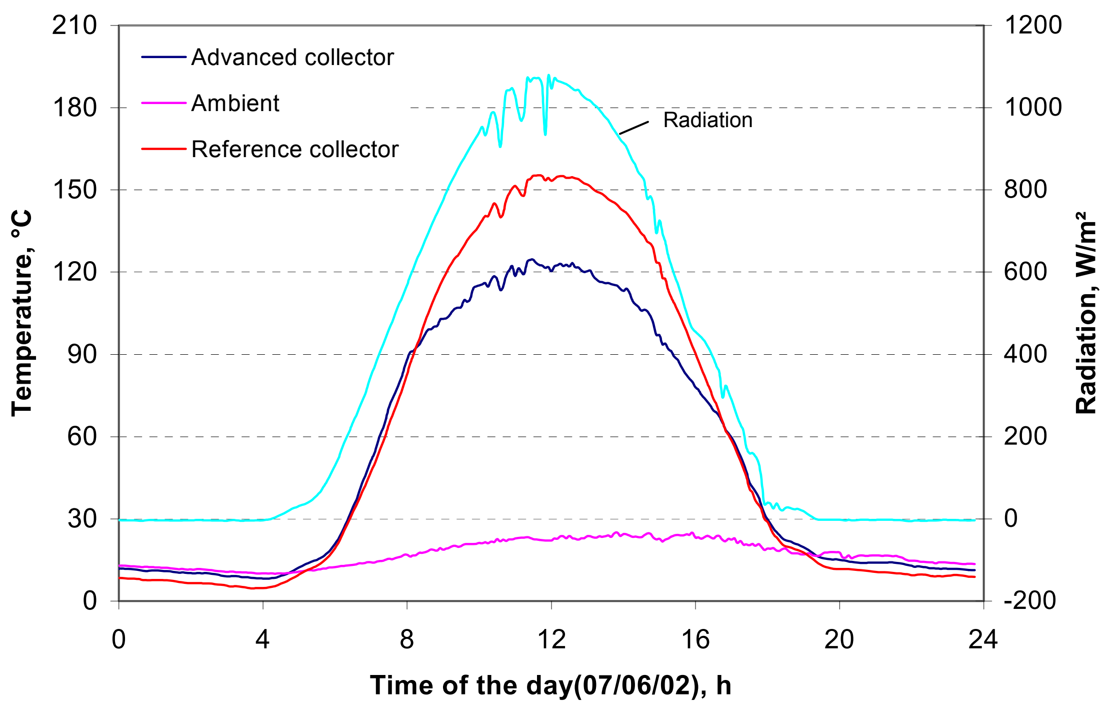

Figure 8: Recorded temperatures and solar radiation intensity on 7th June 2002, (temperatures recorded for the ISTC collector are designated "Advanced Collector").

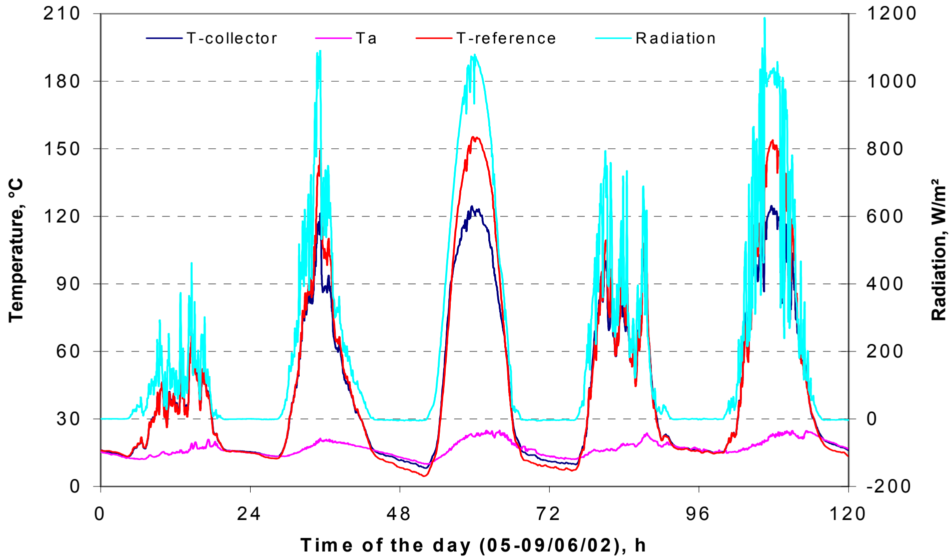

Figure 9: Measurements taken over the period of June 5th – 9th, 2002, (temperatures recorded for the ISTC collector are designated "T-collector").

CONCLUSIONS

During this study, methods to limit stagnation temperatures in flat-plate solar collectors were investigated. As a result, a prototype solar collector incorporation an integral stagnation control feature was built and an experimental investigation carried out to verify its operation under outdoor test conditions. For comparison, a typical collector configuration was tested side-by-side with the ISTC equipped collector. The maximum stagnation temperature in both collectors was recorded under extreme weather conditions. The results show that the heat loss from the ISTC collector was comparable to the reference when the temperature in the collector was below 90-100°C. When the stagnation temperature was above 100°C, the heat loss from the ISTC collector increased and limited the stagnation temperature. Results indicated that at a solar radiation intensity of 1100 W/m^2 and an ambient temperature of 25°C, a collector stagnation temperature of 120-122°C was obtained. These results verify the operation of the ISTC concept and demonstrate that high temperatures in the collector absorber may be limited by this method.

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ACKNOWLEDGEMENT

This study was supported by Enerworks Inc., the Industrial Research Assistance Program of NRCC, NRCan and the Natural Science and Engineering Research Council (NSERC). The support and encouragement of Mr. Michael Noble of Enerworks Inc. is greatly appreciated.