LIMITING STAGNATION TEMPERATURES IN FLAT-PLATE SOLAR COLLECTORS

S.J. Harrison
Qin Lin
L.C.S. Mesquita
Department of Mechanical and Materials Engineering,
Queen’s University, Kingston, ON,
K7L 3N6, Canada

ABSTRACT

Solar collectors may reach high temperatures during power failures or periods when there is minimal heat removal. Under these conditions, “stagnation” temperatures exceeding 170°C can occur within the solar collector. Under these conditions, the collector components and the heat transfer fluid may rapidly degrade and excessive pressures may occur in the collector heat-transfer loop. High collector temperatures can also result in scalding temperatures; a potentially dangerous situation for residents. Recognizing the harmful effects of stagnation, a mechanism for limiting the temperature of solar collectors was developed and tested under typical stagnation conditions. The results of this testing confirmed the operation of a prototype solar collector designed to self-limit its upper temperature. A feature of this design is that the temperature control operates “passively” and requires no user intervention or external power source. An important aspect of this unit is that solar collector operation is not affected during normal (“non-stagnation”) conditions.

1. INTRODUCTION

With most solar water heating systems there is the potential for the solar collectors to reach high temperatures during stagnation conditions [1]. The “thermal loading” resulting from these conditions has been shown to accelerate the degradation of “spectrally selective” absorber coatings used in solar collectors and to contribute to the deterioration of heat transfer fluids used in solar systems. High stagnation temperatures may also result in excessive pressures in the collector loop and scalding temperatures in the hot water storage. This 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 may deteriorate 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 [2, 3]. It is also common practice to shut down the circulation of heat transfer fluid through the solar collectors when the thermal storage reaches a high temperature, however, while this reduces the potential for scalding, it only aggravates the stagnation problem associated with the fluid in solar collectors.

Limiting stagnation temperature has also become a concern with combined photovoltaic and solar thermal collectors (i.e., PVT collectors) as many PV encapsulating and bonding materials have temperature limits below typical stagnation temperatures in many climates [4].

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., “temperature self-limiting”, features. This new design incorporates an Integral Stagnation Temperature Control1, (ISTC). To develop and evaluate this concept, a theoretical and experimental study was conducted and the results are presented in this paper.

1 Patents Pending
1.1 Stagnation Conditions

For the purpose of this paper, “stagnation’ conditions are considered to be any situation under which the solar collector cannot adequately reject absorbed solar heat to its primary heat transfer fluid, thereby causing 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, 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° to the horizontal). These systems are particularly susceptible to high stagnation temperatures in the summer months because of the coincidence of high sun elevations (i.e., low incidence angles [5]) and high ambient air temperatures. Therefore, for the basis of this study, a solar radiation level of 1000 W/m² coincident with ambient temperature of 30°C is was taken as a representative design condition for the stagnation temperature control.

2. STAGNATION TEMPERATURE CONTROL

The thermal performance of conventional solar collectors is well established [5]. Under normal operating conditions, the rate of energy delivery to the load by a solar collector, $Q_{abs}$, 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.,

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

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

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

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.,

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

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,

$$U_L(T_p - T_a) = (\tau \alpha)G$$

(4)

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

$$T_p = T_a + (\tau \alpha)G/U_L$$

(5)

For typical solar collector designs, $(\tau \alpha) = 0.8$ and $U_L = 5.5$ W/m² K. Therefore, for an incident sun intensity of 1000 W/m² and $T_a=30°C$, the stagnation temperature of the absorber, $T_p$, would be 175°C. Similarly, to limit the absorber temperature to less than 120°C, the collector heat-loss coefficient ($U_L$) would have to increase to 8.9 W/m² K.

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 conductance level through the back and sides of the collector case are ~ 1.5 W/m² K.

The top heat loss from a collector depends on the properties of the cover, the absorber coating and the thermal resistance of the air-layer between the absorber and the glass. While it is possible to design a solar collector with a high overall heat loss (e.g., unglazed or single cover with a non-selective, high emittance, absorber coating), and thereby reduce stagnation temperatures, it is common practice to use spectrally-selective absorber coatings to increase solar collector performance at higher temperatures. These latter absorber coatings are characterized by high solar absorptance, $\alpha$, and low infrared emittance, $e$, [5] and will reduce top heat losses from the solar collector but will also increase stagnation temperatures.

For a typical collector design, (e.g., single cover with selective absorber coating) the top heat loss is a function of the absorber plate temperature and reaches 4 W/m² K at 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/m² K, to 8.9 W/m² K whenever the absorber temperature approaches (and exceeds) 120°C. At lower temperatures, the heat loss from the collector should not be affected, i.e., heat losses are minimized during normal operation.

2.1 Integral Stagnation Temperature Control

After extensive analysis and testing [6], it was concluded that the most practical and reliable means for increasing the heat-loss characteristics of a collector during stagnation was
to incorporate cooling channels under the absorber plate. These would introduce ambient air between the absorber plate and the back insulation thereby allowing the natural convection cooling of the collector absorber plate, Fig. 1. These channels must dissipate up to 400 W/m² if the temperature is to be limited under extreme conditions.

To control the flow of air into the channels, a thermally-actuated valve, at the top of the collector opens under stagnation conditions allowing hot air to exhaust from the top and cool ambient air to enter at the bottom of the collector. 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 thereby reducing back heat loss.

The design and geometry of the integral air-channel must be specified to ensure that there is sufficient airflow and heat transfer rates to adequately cool the absorber under stagnation conditions, Fig. 2. The dimensions and tilt angle of the channels affect the natural convection airflow and 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 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 [6].

Fig. 1: Conceptual design of a solar collector with integral stagnation temperature control.

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.

Fig. 2: Cross-section view of a solar collector with integral cooling channels placed below the absorber plate.

2.2 Thermally Actuated Control Valve

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 a desired temperature.

Fig. 3: Rear view of the solar collector showing the thermally activated valve installed at the top.

A variety of thermal actuators could be used to control the valve assembly, but for testing, a sample valve was constructed based on the use of shape memory alloy (SMA) springs [7]. 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, Fig. 2. Through this method, a solar collector with two distinctly different heat loss characteristics could be obtained. In effect, at temperatures below a specified
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.

3. EXPERIMENTAL EVALUATION

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 testing under real environmental conditions Fig. 4.

Fig. 4: Prototype ISTC solar collector with the temperature control feature constructed for this study.

4. TEST RESULTS

A prototype of the ISTC collector was constructed for testing under outdoor environmental conditions. Tests were performed during May-June of 2002 at the Solar Calorimetry Laboratory at Queen’s University in Kingston, Ontario, (Latitude 44° 13’N). The prototype ISTC collector was positioned adjacent to a reference collector to verify the operation of the stagnation control. The reference collector consisted of an identical absorber strip and cover combination but constructed without the ISTC feature. The reference collector 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 oriented 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 a number of thermocouple temperature sensors. Temperatures on the ISTC collector’s absorber and the back insulation plate 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 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 average quantities over 5 minute periods.

Stagnation temperatures in both collectors were monitored over extended periods. Figures 6 and 7 show the maximum temperatures in both collectors and the corresponding solar insolation levels and ambient temperatures for two clear-day tests (May 25th and June 7th). Both the ISTC and reference collectors’ temperatures increased 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 before the temperature reached 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 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 to below 600 W/m², the valve was observed to fully close. After this time, the discrepancy between the collectors’ temperatures disappeared. These experimental results also show the presence of some hysteresis in the operation of the damper valve that resulted in the valve not fully closing until the absorber temperature...
had fallen to approximately 70°C. This is consistent with the operation of the SMA actuator. This effect, while not detrimental, could be minimized though careful selection and manufacturing of the SMA actuator.

The experimental results indicate that the absorber temperatures, and heat loss from both collectors, were effectively identical until the point at which the damper valve opened (at approximately 90°C). With the valve open, the heat loss from the ISTC collector increased and the stagnation temperature reduced relative to the reference collector. Based on these test results, the heat loss ranged between 6.1 - 6.3 W/m² K for the reference collector and 6.1 - 9.6 W/m² K for the ISTC collector. Temperatures recorded for both collectors over the 5-day period from June 5th – 9th are shown in Fig. 8. These results verify the operation of the stagnation control feature 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 temperatures reached by the disabled ISTC collector were slightly higher than those in the reference collector throughout the day. With a solar radiation intensity of 1150 W/m² and an ambient temperature of 25°C, the maximum stagnation temperature was 170°C in the ISTC collector and 160°C in the reference collector.

This result also indicates that the ISTC collector had a lower overall heat loss coefficient than the reference collector at normal operational temperatures (i.e., < 70-80°C). As such, the ISTC feature should have no effect on the performance or annual energy delivery of a solar collector operating under normal (i.e., non-stagnation) conditions.

5. CONCLUSIONS

A method for limiting the stagnation temperature in flat-plate solar collectors was developed and its performance verified in tests conducted under typical “stagnation” conditions. For comparison, a typical solar collector configuration was tested side-by-side with the prototype ISTC equipped collector. The maximum stagnation temperatures in both collectors were recorded over a number of days. Results show that stagnation temperatures in the ISTC equipped collector were over 30 K lower than the reference collector at peak insolation levels.
The results also show that the heat loss from the collector with integral stagnation control (ISTC) was comparable to the reference collector when the temperature in the collector remained below 90°C. When the collector temperature increased above 90°C, the heat loss from the ISTC collector increased and limited the absorber plate temperature. At a solar radiation intensity of 1100 W/m² and an ambient temperature of 25°C, the ISTC collector stagnation temperature was limited to 122°C as compared to 155°C for the reference. These results verify the operation of the ISTC concept and demonstrate that high temperatures in the collector absorber may be limited by this method.

6. REFERENCES


7. ACKNOWLEDGMENTS

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