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Published in:
EuroSun 2010. Book of proceedings

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

THEORETICAL STUDY ON A SOLAR COLLECTOR LOOP DURING STAGNATION

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Abstract

A mathematical model simulating the stagnation behavior of a pressurized solar collector loop with solar collectors with a good emptying behavior is developed. Based on the pre-pressure of the expansion vessel, the system filling pressure of the solar collector loop and the design of the solar collector loop, the mass of the fluid flowing into the pressurized expansion vessel and the pressures at the top part and at the bottom part of the solar collector loop during stagnation for the solar collector loop are calculated. The theoretically calculated results are compared with experimental results. There is a good agreement between calculations and measurements. The developed simulation model is therefore suitable to determine the behavior of solar collector loops during stagnation.

Key words: Solar collector loop; Stagnation

Nomenclature

Symbols

a_1 Heat loss coefficient of a solar collector at $T_e^* = 0$ (W/m^2 K)

a_2 Temperature dependence heat loss coefficient (W/m^2 K^2).

A_c Area of collector/collectors (m^2)

A_{ce} Area of the boiling part of collectors (m^2)

A_{cs} Area of the superheated steam part of collectors (m^2)

C Concentration of propylene glycol/water mixture (%)

$c_{p,l}$ Specific heat of solar collector fluid at constant pressure (J/(kg K))

$c_{p,v}$ Specific heat of vaporized steam in the solar collector loop at constant pressure (J/(kg K))

d_{cm} Inner diameter of the manifolds of solar collectors (m)

d_{st} Inner diameter of the strips of solar collectors (m)

$d_{up,cop}$ Inner diameter of the upper copper pipe of solar collector loop from the outlets of collectors and above the bottom level of the collectors (m)

$D_{up,cop}$ Outer diameter of the upper copper pipe of solar collector loop from the outlets of collectors and above the bottom level of the collectors (m)

$D_{up,ins}$ Outer diameter of the insulation of the upper pipe of solar collector loop from the outlets of collectors and above the bottom level of the collectors (m)

G Solar irradiance (W/m^2)

H Vertical distance between the top and the bottom of solar collector loop (m)

k Thermal conductivity (W/m K)

k_θ Incidence angle modifier, (-)

L_c Length of solar collector (m)

L_{up} Length of the upper pipe of solar collector loop from the outlets of collectors and above the bottom level of the collectors (m)

M_F Mass of the fluid originally occupying the vapor-filled space of the solar collector loop during stagnation (kg)

M_{in} Mass of the propylene glycol/water mixture entered into expansion vessel during stagnation (kg)

M_v Mass of the vapor in the vapor-filled space of the collector loop during stagnation (kg)

$\dot{m}_e$ Mass flow rate of evaporation (kg/s)

$\dot{m}_{cin}$ Mass flow rate of the condensate, which is condensed in upper pipes of solar collector loop, flowing into the boiling parts of collectors via the collector inlets (kg/s)

$\dot{m}_{re,up}$ Mass flow rate of the reevaporated fluid flowing back to the solar collectors from the upper pipe of solar collector loop (kg/s)

$\dot{m}_{re,cm}$ Mass flow rate of the reevaporated fluid flowing back to the superheated steam part from the manifolds of solar collectors (kg/s)

$\dot{m}_{up,tcon}$ Mass flow rate of the condensate condensed in the upper pipes of solar collectors (kg/s)

N_c Number of collectors (-)

$N_{c,st}$ Number of the strips of solar collector (-)

P_1 Pressure of the gas in expansion vessel at the state 1 (Pa)

P_2 Pressure of the gas in expansion vessel at the state 2 (Pa)

P_b Pressure of the bottom part of solar collector loop (Pa)

P_{ba} Pressure of the balloon of the expansion vessel (Pa)

P_t Pressure of the top part of solar collector loop (Pa)

$P_{pre,ba}$ Pre-pressure of the balloon of the expansion vessel (Pa)

$P_{pre,sys}$ system filling pressure of the solar collector loop (Pa)

$q_{ce,he}$ Power supplied to increase the fluid temperature in the boiling part of solar collectors (W)

$q_{ce,sol}$ Thermal power utilizing the solar irradiance in the boiling part of solar collectors (W)

$q_{ce,v}$ Power supplied for the evaporation of the fluid in the boiling part of solar collectors (W)

$q_{cs,he}$ Power supplied to increase the vapor temperature in the superheated steam part of solar collectors (W)

$q_{cs,re}$ Power related to the reevaporation of the condensed steam from the manifolds of solar collectors and the upper parts of solar collector loop (W)

$q_{cs,sol}$ Thermal power utilizing the solar irradiance in the superheated steam part of solar collectors (W)

T_1 Temperature of the gas in the expansion vessel at the state 1 (K)

T_2 Temperature of the gas in the expansion vessel at the state 2 (K)

T_a Ambient temperature (^oC)

T_{cin} Condensate temperature, the condensate is condensed in upper pipes of solar collector loop, flowing into the boiling parts of collectors via the collector inlets (^oC)

T_{ce} Fluid temperature in the boiling part of solar collectors (^oC)

T_{cs} Steam temperature in the superheated steam part of solar collectors (^oC)

T_e Evaporation temperature of the fluid in the solar collectors (^oC)

T^*_{ce} Reduced temperature difference in the boiling part of solar collectors (m^2 K/W)

T^*_{cs} Reduced temperature difference in the superheated steam part of solar collectors (m^2 K/W)

V_0 Empty volume of the expansion

vessel without pressure (m^3)
V_1 Volume of the gas in the expansion vessel at the state 1 (m^3)
V_2 Volume of the gas in the expansion vessel at the state 2 (m^3)
V_c Fluid content of solar collectors (m^3)
W_c Width of solar collector (m)
W_{cms} Width of the metal cover between the manifolds and the cover glass in the solar collector (m)
η_0 Start efficiency of solar collector (-)
η_{ce} collector efficiency at the boiling temperature after considering the incidence angle modifier (-)
η_{cs} collector efficiency at the superheated steam temperature after considering the incidence angle modifier (-)
λ Latent heat of propylene glycol/water mixture (J/kg)

1 Introduction

The behaviour of solar collector loops during stagnation has been studied for many years, since the solar collector fluid in many solar heating systems is protected from critical high temperatures in sunny periods with a possible surplus of solar heat production by switching off the circulation pump. The solar collector fluid in the solar collector evaporates and the solar collector is emptied. Not only can high temperatures during stagnation cause premature decomposition of propylene glycol/water mixtures but also make noises by water hammer from evaporation. Streicher has studied the formation of water hammer and how to minimize the risk of water hammer in solar collector loops with different types of collector connections during stagnation [1]. Poor, good and very good emptying behaviors of solar collector loops were investigated in details by Hausner and Fink [2]. In this paper, the behavior of a solar collector loop with collectors with excellent emptying behavior is theoretically studied and calculated results are compared with measured results from Dragsted et al [3]. The experimental setup shown in fig.1 is investigated by Dragsted et al [3]. The collector loop includes three flat plate collectors which are connected in parallel. The collector is BA30 from Batec Solvarme A/S with a horizontal manifold at the top and at the bottom. 8 parallel strips connect the two manifolds. Metal covers are of aesthetic reasons placed between the collector manifolds and the cover glass. The metal covers will cause a decreased efficiency of the top and bottom of the solar collector. This is considered in the simulation model.

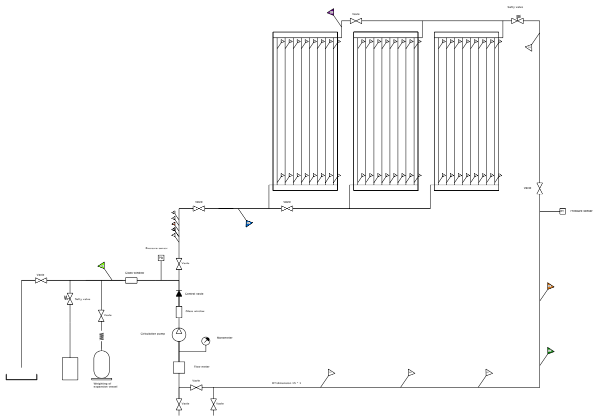

Fig.1 Experimental setup

2.1 Assumptions

The theoretical analysis for a solar collector loop during stagnation is based on the following assumptions:

- The solar collector loop is supposed to be under steady state conditions.
- The solar collectors have a good emptying behavior.

- The solar collectors are divided into two parts. One part is the boiling part in which the temperature of the fluid flowing into the collector from the inlet will increase to the boiling temperature. The other part is the saturated or superheated steam part where condensed fluid flowing back from the upper manifolds of the collectors and the upper pipes of the collector loop will reevaporate.
- The gas inside the expansion vessel and the vapor in the superheated part of the collectors and the upper part of the collector loop are considered to be ideal gas.
- The vapor in the superheated part of the collectors is considered as a steam.
- The system filling pressure is always higher than the pre-pressure of the expansion vessel.

2.2 Equilibrium equations

The solar collector loop shown in Fig.1 is investigated. A propylene glycol/water mixture is used as solar collector fluid. The solar collector loop is supposed to be under steady state conditions during stagnation. The solar collectors are divided into a boiling part in the bottom of the collectors and a saturated or superheated steam part in the top of the collectors. The vapor from the boiling part will become superheated steam when the solar irradiance is higher than required for evaporation and the steam will move to the upper part of the collectors. The temperature of the steam will decrease and the steam will condense in the top manifolds due to the metal covers above these manifolds. The condensed fluid in the upper manifolds will flow back to the superheated steam part of the collectors and reevaporate. Steam will flow into the upper pipes of the solar collector loop from the outlets of the collectors and a part of the steam will condense there. A part of the condensed fluid in the upper pipes of the collector loop will flow back into collectors through the collector outlets and the rest of the condensed fluid will push the fluid in the solar collector loop forward so that the solar collector fluid will enter the collectors through the collector inlets at the bottom of the collectors.

2.2.1 Boiling parts of collectors

In the lower parts of collectors the propylene glycol/water mixture is evaporated. The solar irradiance is used to increase the fluid temperature to the boiling temperature and to evaporate the fluid. The thermal energy equilibrium equation is:

$$q_{ce,sol} = q_{ce,v} + q_{ce,he} \tag{1}$$

2.2.2 Superheated steam parts of collectors

In the upper parts of collectors the power received from solar irradiance is equal to the power used to increase the temperature of the steam and the power used to reevaporate the condensed fluid from the upper manifolds of the collectors and the upper pipes of a solar collector loop:

$$q_{cs,sol} = q_{cs,he} + q_{cs,re} \tag{2}$$

2.2.3 Solar collector loop

According to the mass conservation law, the mass of the fluid which originally occupies the vapor-filled space of the collector loop inclusive the collectors during stagnation must be equal to the sum of the mass of vapor in the collector loop inclusive the collectors during stagnation and the mass of propylene glycol/water mixture entered into the expansion vessel during stagnation:

$$M_F = M_v + M_{in} \tag{3}$$

Furthermore, the mass flow rate of vapor evaporating from the fluid in the bottom of the collectors is equal to the mass flow rate of the fluid, which is condensed in the upper pipes of solar collector loop and is pushing fluid forward into the collector through the inlets at the bottom of the collectors:

$$\dot{m}_e = \dot{m}_{cin} \quad (4)$$

2.3 Equations used in simulation model

In the following sections the most important equations used for the simulation models are presented. The model solves the equations to determine temperatures and pressures in different parts of the solar collector loop as well as the mass of the fluid evaporated in the collectors and the fluid pushed into the expansion vessel.

2.3.1 Boiling parts of the collectors

In the boiling parts of the collectors, the following equations are used:

$$q_{ce,sol} = GA_{ce}\eta_{ce} \quad (5\text{-}1)$$

$$q_{ce,v} = \dot{m}_e\lambda \quad (5\text{-}2)$$

$$q_{ce,he} = \dot{m}_e c_{p,l}(T_e - T_{cin}) \quad (5\text{-}3)$$

where η_{ce} can be calculated by:

$$\eta_{ce} = k_\theta\eta_0 - a_1T^*_{ce} - a_2G{T^*_{ce}}^2 \quad (5\text{-}4)$$

The reduced temperature difference, T^*_e, is determined by:

$$T^*_{ce} = (T_{ce} - T_a)/G \quad (5\text{-}5)$$

2.3.2 Superheated steam parts of the collectors

In the steam part of the collectors, the following equations are used:

$$q_{cs,sol} = GA_{cs}\eta_{cs} \quad (6\text{-}1)$$

$$q_{cs,he} = \dot{m}_e c_{p,v}(T_{cs} - T_e) \quad (6\text{-}2)$$

$$q_{cs,re} = (\dot{m}_{re,up} + \dot{m}_{re,cm})c_{p,v}(T_{cs} - T_e) + (\dot{m}_{re,up} + \dot{m}_{re,cm})\lambda \quad (6\text{-}3)$$

The collector efficiency at the superheated steam temperature, η_{cs}, can be calculated with equation (5-4) but the reduced temperature difference used in equation (5-4) is here substituted with T^*_{cs}:

$$T^*_{cs} = (T_{cs} - T_a)/G \quad (6\text{-}4)$$

2.3.3 Expansion vessel

There is a balloon with gas inside the expansion vessel. When the state of the gas inside the balloon changes from one to another, the behavior of the gas obeys the ideal gas law:

$$P_1V_1/T_1 = P_2V_2/T_2 \quad (7)$$

2.3.4 Other parts of the solar collector loop

The vapor flowing out of the solar collectors will move to the upper pipes of the solar collector loop and condense there. Some of the condensate will flow back to the collectors via the top outlets and the rest of the condensate will push the fluid in the solar collector loop forward so that solar collector fluid will enter the collectors from the bottom inlets. The following equation is used:

$$\dot{m}_{re,up} = \dot{m}_{up,tcon} - \dot{m}_{cin} \quad (8)$$

3 Validations of the model

3.1 Parameters for theoretical calculations

If the detailed dimensions and efficiency of the solar collectors, the design of the solar collector loop, the length and insulation of the upper pipes in the solar collector loop, the pre-pressure of the expansion vessel and the system filling pressure, the percentage of the propylene glycol/water mixture, the ambient temperature and the solar irradiance are known, the mass of propylene glycol/water mixture entered into the expansion vessel, the height of the boiling parts of the collectors, the boiling and stagnation temperatures in the collectors and the pressures in the different parts of the solar collector loop can be calculated by means of the model. The parameters corresponding to a solar collector loop investigated experimentally [3] and used in the theoretical calculation are shown in table 1.

Table 1. Parameters for theoretical calculations

η_0 (-)	0.772	d_{cm} (m)	0.020	k (W/m K)	0.04	$P_{pre,sys}$ (bar)	1.068
a_1(W/m^{2}K)	2.907	W_{cms} (m)	0.071	$D_{up,cop}$ (m)	0.015	V_0 (litre)	20.6
a_2(W/m^{2}K^2)	0.015	A_c (m^2)	3.0	$D_{up,ins}$ (m)	0.029	H (m)	6.4
L_c (m)	2.68	V_c (litre)	2.26	$d_{up,cop}$ (m)	0.013	C (%)	32
W_c (m)	1.13	N_c	3	L_{up} (m)	5.73		
d_{st} (m)	0.0095	$N_{c,st}$	8	$P_{pre,ba}$ (bar)	1.034		

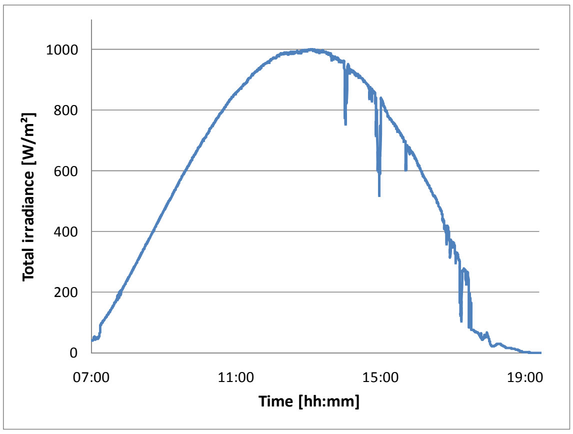

Fig.2 Total solar irradiance on solar collector, September 1, 2009

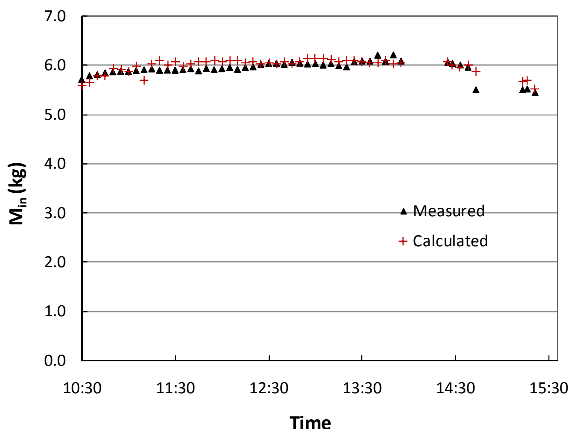

Fig.3 Measured and calculated mass of solar collector fluid entered into the expansion vessel during stagnation, September 1, 2009

3.2 Measurements under steady state conditions

The above mentioned solar collector loop was investigated during a stagnation period. Since the theoretical model assumes steady state conditions, measured data used for comparison with theoretically calculated results must be for steady state conditions or as close to steady state conditions as possible. This is achieved on September 1, 2009. Fig.2 shows the measured total solar irradiance on the collector on September 1, 2009.

3.3 Comparisons between calculated and measured results

Fig.3 shows the calculated and measured mass of propylene glycol/water mixture entered into the expansion vessel during stagnation September 1, 2009. Fig.4 and 5 show the calculated and measured pressure at the bottom part of the solar collector loop and at the upper part of the solar collector loop during stagnation.

From the figures it can be seen that the calculated results are in good agreement with the measured data on September 1, 2009. The average values of the relative differences between the calculated and measured results of M_{in}, P_b, and P_t are 2%, 1% and 3%, respectively, for the stagnation period.

The agreement between measured and calculated quantities is also good for other pressure conditions for the expansion vessel and the solar collector loop. The simulation model is therefore suitable for analyzing the behavior of different solar collector loops.

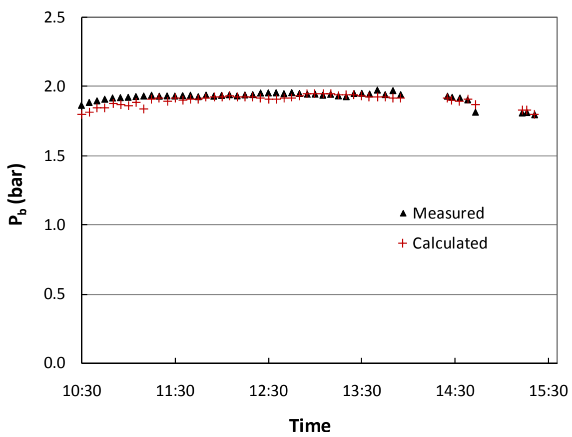

Fig.4 Measured and calculated pressure of the bottom of the solar collector loop during stagnation, September 1, 2009

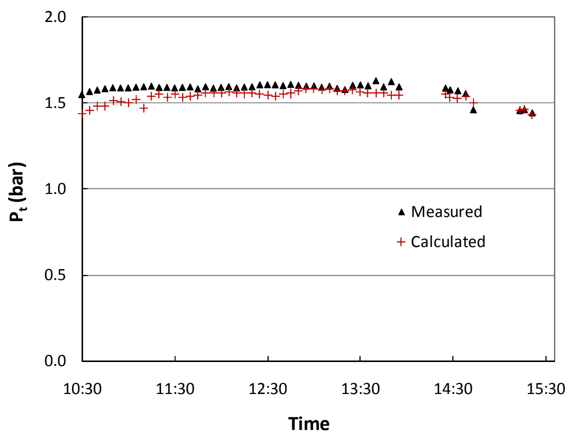

Fig.5 Measured and calculated pressure of the top of the solar collector loop during stagnation, September 1, 2009

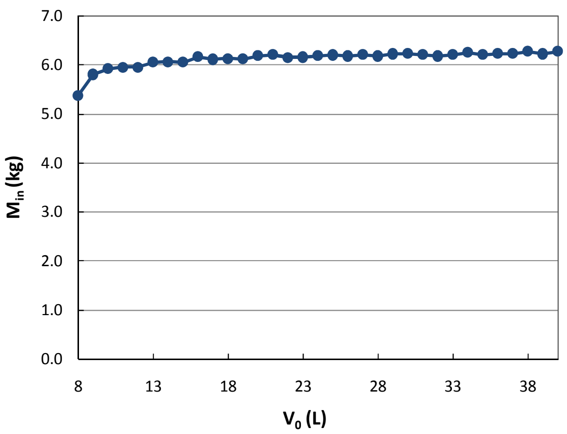

Fig.6 Mass of solar collector fluid entered into the expansion vessel as function of the expansion vessel volume

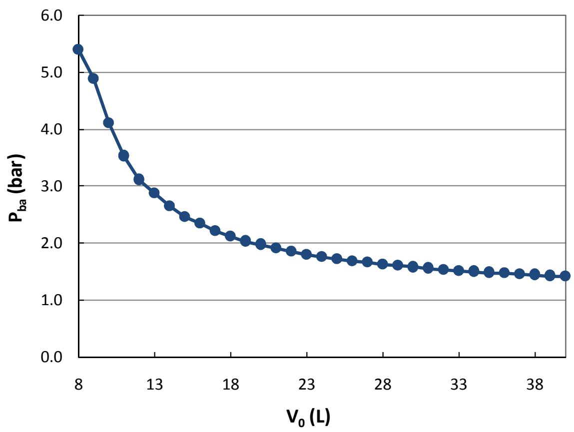

Fig.7 Pressure of the balloon in the expansion vessel as function of the expansion vessel volume

4 Influence of the volume of expansion vessel on the behavior of the solar collector loop during stagnation

Calculations are carried out with the simulation model of the solar collector loop described in section 3 during a stagnation period. The following assumptions are used: The ambient temperature is 25^{o}C, solar irradiance is 1000W/m^2, the pre-pressure of the expansion vessel is 1.0 bar and the system filling pressure of the system is 1.05 bar. Fig.6 and 7 show the mass of propylene glycol/water mixture entered into the expansion vessel and the pressure of the balloon in the expansion vessel during stagnation for different volumes of the expansion vessel.

If the volume of the expansion vessel is higher than 13 litres, the mass of propylene glycol/water mixture entered into the expansion vessel during stagnation will increase very slowly with increase of the volume of the balloon. The air pressure of the balloon inside the expansion vessel, will vary slowly with the increase of expansion vessel volume if this volume is higher than 13 litres. If the volume is lower than 13 litres the pressure will increase sharply by decreasing expansion vessel volume.

5 Conclusions

The investigations show that

- The developed simulation model is suitable to characterize solar collector loops during stagnation as long as the solar collectors have a good emptying behaviour.
- If the volume of the expansion vessel is bigger than a certain volume, the mass of propylene glycol/water mixture entered into the expansion vessel during stagnation will not increase much and the pressure of the air in the balloon of the expansion vessel will not decrease much for increased expansion vessel volume.

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