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HYDRODYNAMIC MODEL FOR HORIZONTAL AND INCLINED SOLAR ABSORBER TUBES FOR DIRECT STEAM GENERATION COLLECTORS

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ABSTRACT

Direct steam generation collectors are considered with the aim to improve the performance and reduce operating costs of solar electric generation systems. In this study a hydrodynamic model is developed to investigate the flow conditions of once-through direct steam generation (DSG) solar collectors. The hydrodynamic model comprises two main parts: flow pattern and pressure drop prediction. Flow pattern maps in typical DSG collector horizontal and inclined absorber tubes are generated. Two-phase flow frictional pressure drop correlations for the range of operating conditions DSG collectors are selected by comparison with experimental data for steam-water flow at conditions similar to the direct steam generation collectors. Pressure drop is evaluated for different operating conditions for both horizontal and inclined solar absorber tubes.

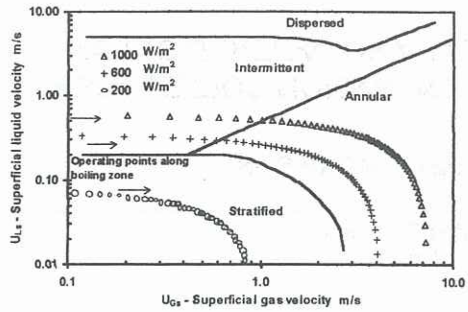
INTRODUCTION

Solar electric generation systems (SEGS) currently in operation consist of many parallel parabolic trough collectors with a single phase heat transfer fluid circulating through the collector loop. The heat transfer fluid is fed to a heat exchanger where steam is generated for use in a Rankine cycle turbine. To improve the performance and reduce costs, direct steam generation (DSG) in the collector has been proposed (Müller, 1991, Cohen and Kearney, 1994). The flow in a DSG collector consists of water and steam mixtures (eg., two phase flow) in a very long horizontal pipe or a segmented inclined pipe. Control of flow pattern in the absorber tube is critical since the existence of flow stratification may introduce large circumferential temperature gradients in the absorber tube wall and possible damage to the absorber module. Ajona et al. (1996) reported that stratified flow in a steel tube DSG collector causes a temperature difference of up to 50 K around the absorber tube wall while annular flow produces a temperature difference of only 3 K. A large circumferential temperature difference causes the absorber tube to bend and possibly break the vacuum space glass envelope and thus increase the collector thermal loss. Thus to evaluate the performance of a DSG collector in a power plant, a model of the flow conditions in the absorber tube is required. A DSG collector thermal model developed by Odeh et al. (1998) to evaluate thermal efficiency and flow properties along a typical solar absorber tube is extended in this study to include flow pattern and pressure drop calculations. The flow pattern analysis is based on the two-phase flow model developed recently by Taitel (1990). To evaluate pumping power of horizontal and inclined solar absorber tubes, the hydrodynamic model must also evaluate pressure drop in the single phase and two phase flow zones. The Martinelli-Nelson (1948) frictional pressure drop correlation for DSG collector operating conditions is compared with experimental data for high pressure steam-water flow in horizontal and vertical pipes reported by Manzano et al. (1987) and Antipov (1992).

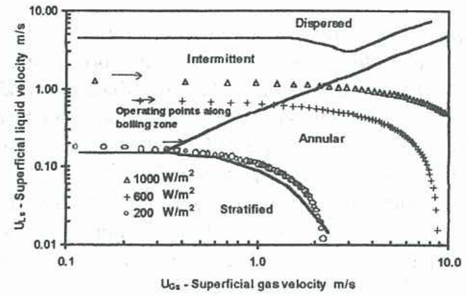
FLOW PATTERN MODEL

Many studies have been carried out to develop transition models for two-phase flow. A summary of these models given by Taitel (1990), in the form of a unified model for predicting flow pattern transition, is adopted in this study and incorporated in the thermal model of a DSG collector developed by Odeh et al. (1998) to evaluate the flow patterns along the absorber tube for different operating conditions.

Flow pattern maps are generated for the boiling zone in horizontal and 10° inclined collector absorber tubes. The flow regimes considered in these maps are; stratified, annular, dispersed bubble and intermittent (slug or plug). Flow pattern maps for 54 mm and 38 mm inner diameter horizontal collector absorber tubes are shown in Figs. 1a and 1b. The operating point trajectory of gas and liquid superficial velocities along a typical absorber tube is also shown in Fig. 1 for beam radiation of 200 W/m^2 to 1000 W/m^2. The points marked on the trajectories in Figs. 1a and 1b represent exit superficial velocities in each 6 m long segment of the absorber tube boiling zone. For the smaller absorber tube diameter a typical operation characteristic shifts away from the stratified region toward the intermittent and annular regions, however stratified flow will occur at low radiation levels. For the larger absorber tube diameter (54 mm) there is a possibility of stratified flow at low radiation levels which would cause large temperature gradients around the circumference of the absorber and possible tube failure (Ajona et al., 1996). The flow patterns for an inclined absorber tube DSG collector shown in Figs. 2a and 2b differ significantly from the flow patterns for a horizontal collector and show that there is no possibility of stratified flow occurring in an inclined collector. The absorber tube diameter has a significant effect on the flow pattern for low radiation levels with the flow tending to be more intermittent for large absorber tube diameters.

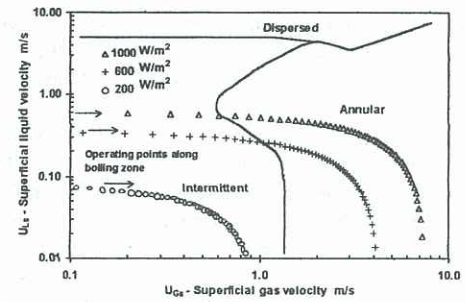


(a) Tube diameter = 54 mm

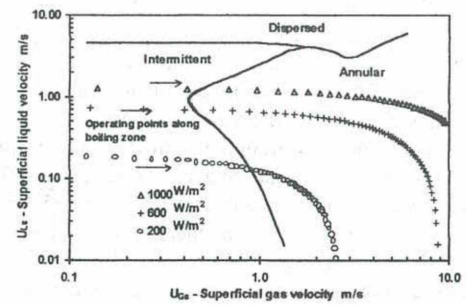


(b) Tube diameter = 38 mm

Figure 1: Flow pattern maps and operating characteristics for horizontal DSG collector absorber tube, water- steam, P_{in}= 100 bar, T_{in}=210 °C, T_{exit}=540 °C, (a) D_i= 54 mm, (b) D_i=38 mm.



(a) Tube diameter 54 mm



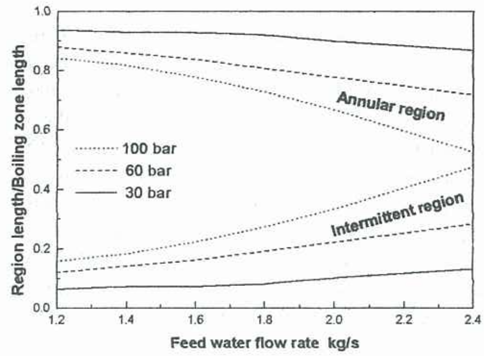
(b) Tube diameter 38 mm

Figure 2: Flow pattern maps and operating characteristics for 10° inclined DSG collector absorber tube, water-steam, P_{in}= 100 bar, T_{in}=210 °C, (a)D_i= 54 mm, (b)D_i= 38 mm.

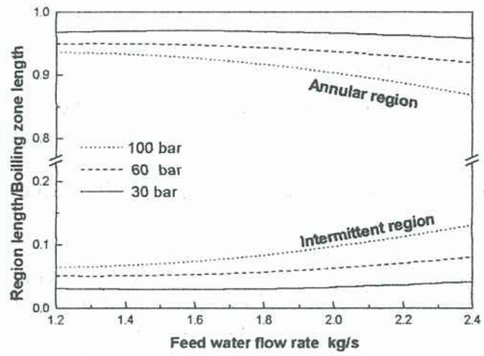
For both the horizontal and inclined collectors shown in Figs 1 and 2 dispersed bubble flow occurs only at very high superficial liquid velocities which do not occur during normal operation of a DSG collector.

EFFECT OF OPERATING CONDITIONS ON FLOW PATTERNS

For a given beam radiation, the collector exit condition depends on the feed water flow rate which affects the water level and thus the flow pattern in the boiling zone. Typical operation of a DSG collector assembly generating dry saturated steam at 100 bar for beam radiation of 1000 W/m² requires a feed water flow rate of 1.25 kg/s. The effect of feed water flow rate on the flow pattern distribution in horizontal and inclined absorber tubes is shown in Figs. 3a and 3b (variable exit steam quality).



(a) Horizontal absorber tube



(b) Inclined absorber, 10°

Figure 3: Flow pattern distribution versus feed water flow rate in the boiling zone of a DSG collector, T_{in} =210 °C, 600 m long, D_i = 54 mm, radiation 1000 W/m².

As the feed water flow rate increases the annular region length decreases and the intermittent region length increases due to the decrease in steam quality and increase in water level. Thus as the DSG collector generates higher quality steam the flow pattern shifts toward annular flow and the absorber tube circumferential temperature gradients reduce. Collector inclination has a significant effect on flow pattern and the annular flow region becomes dominant. This is because the increase of gravity force on the flow with collector inclination reduces wave formation. The intermittent region length increases with working pressure due to the decrease in void fraction (steam/water area ratio).

PRESSURE DROP

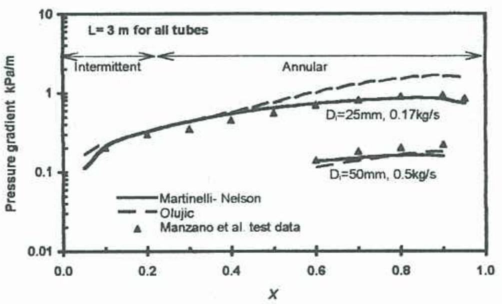
The pumping power required to circulate working fluid through the absorber is a significant factor in the overall performance of an oil based solar electric power generation plant, however for a DSG collector the mass flow rates and hence pumping power will be significantly lower. The pressure gradient (dp/dz) in a DSG collector consists of three components: the acceleration pressure gradient $(dp/dz)_{acc}$, gravitational pressure gradient $(dp/dz)_{grav}$ and frictional pressure gradient $(dp/dz)_{frc}$. The total pressure gradient is given by,

$$\left(\frac{dp}{dz}\right) = \left(\frac{dp}{dz}\right)_{frc} + \left(\frac{dp}{dz}\right)_{acc} + \left(\frac{dp}{dz}\right)_{grav} \qquad (1)$$

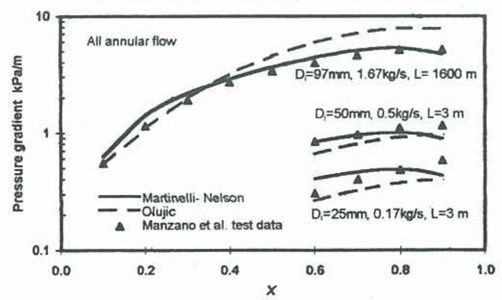
The pressure gradient at any point in the absorber can be evaluated by selecting appropriate correlations for single phase (water or steam) and two-phase flow (boiling).

TWO PHASE ZONE PRESSURE GRADIENT

Few studies in the literature report measured frictional pressure drop in steam-water flow at high pressures, and low mass fluxes applicable to a DSG collector. Stephan (1992) recommended the Martinelli-Nelson (1948) correlation for low mass flow, typical of DSG collector operating conditions. Michael et al. (1995) recommended Olujic's (1985) correlation for high gas and low liquid velocity conditions (typical of a DSG collector). Martinelli-Nelson and Olujic's correlations were compared with experimental data for steam flow at high pressure in horizontal and vertical pipes with mass flux similar to that for a DSG collector and are shown in Figs. 4 and 5.



(a) Short tube test data, P=100 bar



(b) Short and long tube test data, P= 20 bar

Figure 4: Comparison between frictional pressure gradient by Martinelli-Nelson (1948) and Olujic (1985) correlations and Manzano et al. (1987) test data for steam-water flow in a horizontal pipes. (a) 100 bar (b) 20 bar.

The Martinelli-Nelson correlation shows good agreement with the steam- water test data at different steam quality (x) and in most conditions performs better than the Olujic (1985) correlation. The majority of the flow patterns for the data shown in Figs. 4 and 5 are annular. Since annular flow is required in a DSG collector, it may be concluded that acceptable prediction of pressure drop in the collector can be achieved using the Martinelli- Nelson correlation.

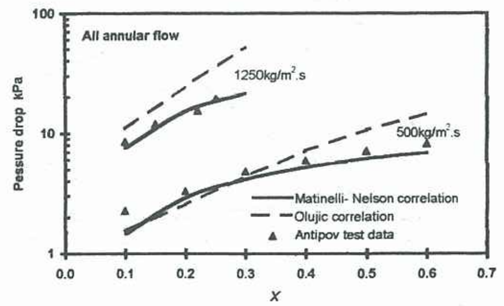


Figure 5: Comparison of friction pressure drop correlation by Martinelli-Nelson (1948) and Olujic (1985) with Antipov (1987) test data for mass flux of 500 and 1250 kg/m^2 s in a vertical pipe, P= 60 bar, D_i = 13 mm, and L =0.975 m.

EFFECT OF OPERATING CONDITIONS ON PRESSURE DROP

The major factors affecting pressure drop in a DSG collector are feed water flow rate, absorber tube diameter, absorber tube length, working pressure and absorber tube inclination. The pressure drop in a typical absorber tube for different operating pressures is shown in Fig. 6. This collector would generate steam when the feed water flow rate is below 1.25 kg/s. At this feed water flow rate the pressure drop at a working pressure of 30 bar is five times the pressure drop at a working pressure of 100 bar. The trend of pressure drop with feed water flow rate also varies with working pressure due to changes of the extent of the different phase regions.

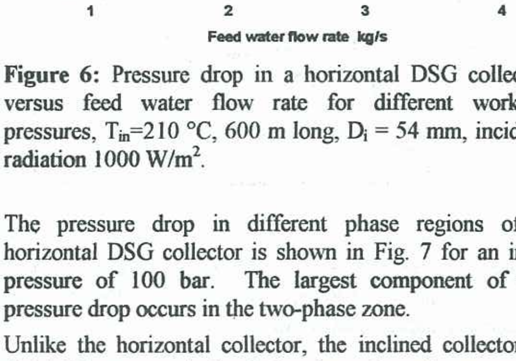


Figure 6: Pressure drop in a horizontal DSG collector versus feed water flow rate for different working pressures, T_{in}=210 °C, 600 m long, D_i = 54 mm, incident radiation 1000 W/m^2.

The pressure drop in different phase regions of a horizontal DSG collector is shown in Fig. 7 for an inlet pressure of 100 bar. The largest component of the pressure drop occurs in the two-phase zone.

Unlike the horizontal collector, the inclined collector is divided into many inclined absorber tube units connected together by joining pipes. The total length of these joining pipes in a typical inclined collector (600 m long absorber) is 104 m. Thus the main difference in pressure drop between the inclined and horizontal collector assemblies is due to the pressure drop in the joining pipes as shown in Fig. 8.

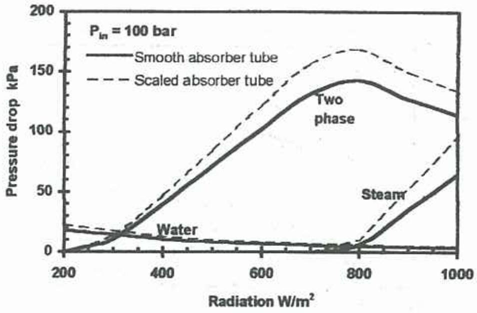


Figure: 7 Pressure drop in different phase regions in a horizontal absorber tube versus radiation, $L_{collector}$=600 m, P_{in}=100 bar, T_{in} =210°C, D_i = 54 mm, flow rate 0.95 kg/s.

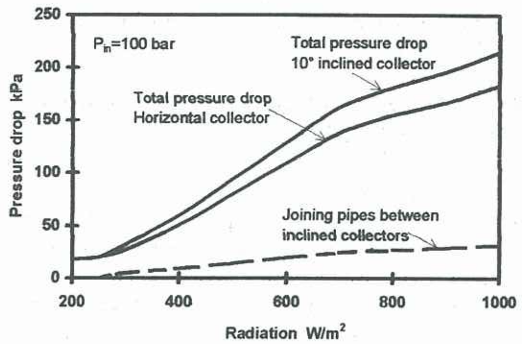


Figure: 8 Pressure drop in horizontal and 10° inclined absorber tubes, (conditions similar to Fig. 7).

Pressure drop variation with feed water flow rate in each phase region is shown in Fig. 9. Total pressure drop is maximum when feed flow rate is 1.5 kg/s and collector is generating saturated steam (no dry steam zone). The data shown in Fig. 9 indicates that there is a region of possible hydrodynamic instability due to adverse pressure gradients in the critical region between the points P_{c1} and P_{c2}.

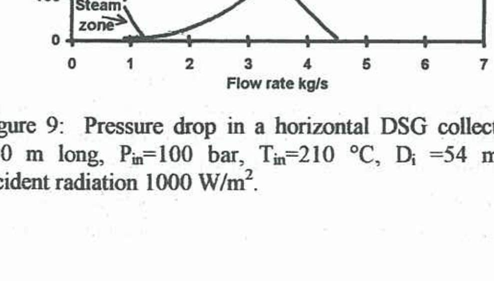


Figure 9: Pressure drop in a horizontal DSG collector, 600 m long, P_{in}=100 bar, T_{in}=210 °C, D_i =54 mm, incident radiation 1000 W/m^2.

CONCLUSION

The uncertainties associated with the two phase flow or boiling in the DSG collector absorber tube have been clarified by the hydrodynamic model of this study. Flow pattern analysis showed that the inclined absorber tube has lower probability of stratified and intermittent flow than a horizontal tube at high incident radiation. However, low radiation causes an increase in stratified flow for a horizontal collector and an increase in intermittent flow for an inclined collector. Thus operating conditions such as feed water flow rate, pressure and inlet temperature should be selected so that annular flow is always dominant to avoid high temperature gradients in the absorber tube wall caused by stratified flow and water hammer caused by the intermittent flow. At high beam radiation, as steam quality at the collector exit increases better flow patterns are achieved.

Pressure drop in an inclined absorber tube collector was found to be higher than a horizontal absorber tube due to the effect of pressure drop in the joining pipes. Pressure drop gradient instability is a possible problem in both horizontal and inclined DSG collectors.

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