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International Journal of Multiphase Flow 30 (2004) 763–777
International Journal of Multiphase Flow
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# Evaporation in parallel pipes—splitting characteristics ☆

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Received 20 September 2003; received in revised form 29 March 2004

**Abstract**

Utilizing solar power using parabolic trough collectors for energy is considered most proven and lowest cost for large-scale solar power technology. So far commercial plants used oil as the primary heated fluid and steam was produced in a secondary heat exchanger. This seem to be a very inefficient process due to the need of extra heat exchangers and extra losses incurred while heat is transferred from oil to steam. The reason oil is used as the primary heated fluid is partially due to the reluctance of the designer to deal with the behavior of two-phase, water steam, in parallel pipes owing to the possible uneven flow distribution and instability related problems.

Analysis of a system of two parallel pipes with common inlet and outlet manifolds that undergoes a process of heating and evaporation shows that multiple steady state solutions for the flow distribution in the two pipes may be obtained. A simplified stability analysis backed by new experimental results allows the determination of the actual physical solutions that take place. Design considerations are discussed and suggestions for optimal operation are included.


*Keywords:* Parallel pipes; Evaporation; Solar energy; Two-phase

## 1. Introduction

Simultaneous flow of two phases in parallel pipes has many engineering applications. Fluids flowing in parallel pipes, undergoing evaporation or condensation take place in heat exchangers, boilers and condensers in power plants and cooling systems. In the nuclear industry, two-phase

☆ It is our great pleasure to take part in this special issue and to congratulate George Yadigaroglu on the occasion of his 65th birthday. We have known George for more than 20 years, and greatly respect his activity and scientific achievements. Moreover, we have found George as an ultimate gentleman and a very warm friend. We wish George many more productive, enjoyable and happy years.

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doi:10.1016/j.ijmultiphaseflow.2004.04.006

flow in parallel channels is of major interest related to the loss of cooling accident (LOCA) when a break in the cooling water supply takes place and emergency cooling water is used to cool the core. Two phase flow in parallel micro-channels is used for heat removal in modern micro-electronic devices.

The main motivation for the present work is related to the use of solar energy based on an array of parallel heated pipes. In this case an array of parallel pipes is constructed, each at the focal center of parabolic mirrors that focus solar radiation on the heated pipes. The pipes are placed at the center of glass pipes, under vacuum conditions, which allows radiant heat to reach the pipes but minimizes convective and radiant losses to the surroundings. Since the objective of this system is to produce steam one would expect that water should enter the inlet manifold and steam will be produced in the heated pipe. However, commercial plants used oil as the primary heated fluid and steam was produced in a steam generator. The reason direct steam generation (DSG) was not used before is due to the lack of understanding of two-phase flow behavior within the absorbing pipes and the fear of possible occurrence of circumferential temperature distribution, instabilities and non-even flow distribution.

A comprehensive review of flow instability in a single heated pipe is included in the papers of Kakaç and Veziroglu (1983), Yuncu and Kakaç (1988) and Pederson and May (1982) where the last one is concerned specifically with solar energy. The instabilities are classified as static instability and dynamic instability.

Static instability was first described by Ledinegg (1938) and it is based on the behavior of the pressure difference in a pipe as a function of the flow rate. In a heated pipe that undergoes evaporation one may have regions where the pressure drop decreases with increasing flow rate. In this regions steady state solutions may be unstable.

The main dynamic instabilities are density instability and pressure drop instability. Density instability results from a dynamic oscillation related to void fraction waves. It manifests itself in the up slopping branch of the pressure drop vs. the flow rate curve. Pressure instability causes oscillations around the steady state solutions along the negative slopping of the pressure drop curve provided that these steady states are statically (Ledinegg) stable. Also for pressure drop oscillations to occur, compressible volume in the pipe or in a surge tank should be available. Accurate analysis for the prediction of density and pressure drop oscillations are quite difficult. Nevertheless simplified approaches are summarized in Kakaç and Veziroglu (1983) and Yuncu and Kakaç (1988).

In contrast to the considerable research related to flow in a single heated pipe, relatively few articles deal specifically with multiple parallel pipe-flow. Akagawa et al. (1971) investigated flow distribution and stability for the case of Freon −113 flowing in three parallel vertical tubes. A simplified stability analysis was performed and was shown to compare favorably with the experimental results. Ozawa et al. (1979a) performed a similar experiment with Freon 113 in a five vertical pipe system. They observed density oscillations in the range where the pressure drop vs. flow rate increases monotonically and uneven distribution in the range where pressure drop vs. flow rate decreases. Nakanishi et al. (1983) performed evaporation tests with Freon 113 on a system of 5, 4 and 3 vertical parallel pipes. Their main conclusion is that if the flow is distributed uniformly among all channels, they oscillate with the same amplitude and equal phase lag. They performed an additional study on air water flowing in two parallel horizontal pipes and were able to obtain oscillations only when the lines were connected to compressible volumes. They did comment that results obtained for air water should not directly apply to actual boiling systems.

Ozawa et al. (1979b, 1982, 1989) studied experimentally two-phase, water–air flow in capillary parallel pipes of 2.0 to 3.1 mm diameter, 3.1 m long. They attempted to simulate flow in boiling channels by the injection of air along the pipes. For the case of low and high total gas flow rates (for a constant total liquid flow rate) the splitting ratio was indeed equal. But for intermediate gas flow rates uneven splitting of the gas was observed with little variation in the liquid flow rate. This phenomenon was explained on the basis of multiple steady state solutions followed by a stability analysis.

Jović et al. (1994) investigated experimentally the onset of pressure drop oscillations in two phase air water flow in three parallel vertical channels of annular cross section. The fluids were fed separately to each pipe while the exit was common. It was shown that oscillatory instabilities may occur in one, two or all three channels while the other channels and the main loop may exhibit stable operation.

Reinecke et al. (1994) considered flow reversal in vertical two-phase water–air flow in parallel channels that is related to loss of coolant accident (LOCA) in nuclear plants. Their experimental set up consists of six tubes connecting a top and a bottom plenum. The two-phase mixture was fed into the bottom plenum and experiments were carried out to determine the boundaries of the reversal state. A model, based on pressure drop calculations was presented for the prediction of the reversal boundaries.

Tshuva et al. (1999) investigated the splitting of adiabatic two-phase flow in a system of two parallel pipes with a common feed and a common exit. They showed that for low flow rates and in inclined pipes the flow is not symmetric and may take place only in one pipe while stagnant liquid is present in the other pipe. The actual situation was fairly well predicted using steady state solutions and assuming that the flow configuration will be the one that results in a minimum pressure drop. This assumption was recently confirmed by Shirai and Ninokata (2001).

Renewed interest in solar energy production based on the parabolic trough concept stimulated intensive research in this area. May and Murphy (1983) used the homogeneous model to analyze the benefits of the direct generation of steam in line-focus solar collectors. Almanza and Lentz (1998), Almanza et al. (2002) and Odeh et al. (2000) were concerned with the flow pattern in the heated pipe and the circumferential temperature gradient that is generated during stratified flow. Temperature difference between the upper and the lower sides of the absorber may cause structural failure and it is considered one of the major problems in DSG operation. Natan et al. (2003) analyzed a system of two parallel pipes with common inlet and outlet manifolds that undergoes a process of heating and evaporation. The results show that the solution is not unique and one can obtain multiple solutions even for the case of equal heating of the two pipes.

Flow in real large-scale experiments of a single pipe DSG operation is described by Zarza et al. (2002), Eck and Steinmann (2002) and Price et al. (2002). These papers bring to our attention the up-to-date status of the PSA (Plataforma Solar de Almeria) experimental results. Apparently the flow in parallel pipes is still not well analyzed (Lippke, 1996; Zarza et al., 2002).

It is the purpose of this work to analyze a system of evaporating fluid flowing in parallel horizontal and slightly inclined pipes with common inlet and outlet manifolds. Attention is focused on a relatively simple system, which contains only two parallel pipes. Experimental data on a heated single pipe and two parallel pipes are collected and compared with the analysis. Some design criteria for parallel flow are outlined.

## 2. Experimental facility

A schematic diagram of the experimental facility is presented in Fig. 1. The system consists of two stainless steel parallel pipes with a common inlet manifold. Both pipes are open to the atmosphere at the exit. Each pipe has a diameter of 5 mm and is 6 m long. The whole flow system can rotate upwards within the range of 0–30°.

Each pipe is imbedded in a Magnesium oxide (MgO) powder. Heating elements surround the Magnesium oxide layer and are insulated from the surroundings. Total power available for each pipe is 24 kW.

Subcooled water that enters the inlet manifold splits into the two parallel pipes. At the exit the water can be in the liquid phase, two-phase or superheated vapor, depending on the heating power and flow rate. Separators constructed at each pipe exit allow the collection and the measurement of the liquid while the vapor is damped outside. A constant displacement gear pump is used and the flow rate is controlled by a frequency controller. The range of the total flow rate is 0.1–6 l/min. The inlet water temperature is measured by a resistant temperature detector, RTD (Accuracy $\pm 0.5$ °C).

The main objective of the experiment is to collect data on the splitting characteristics of the flow rate in the two pipes, the inlet pressure and the exit temperature for each pipe. Flow rates and inlet pressure for each pipe are measured with Toshiba magnetic flow meter ($\pm 0.007$ l/min) and STS

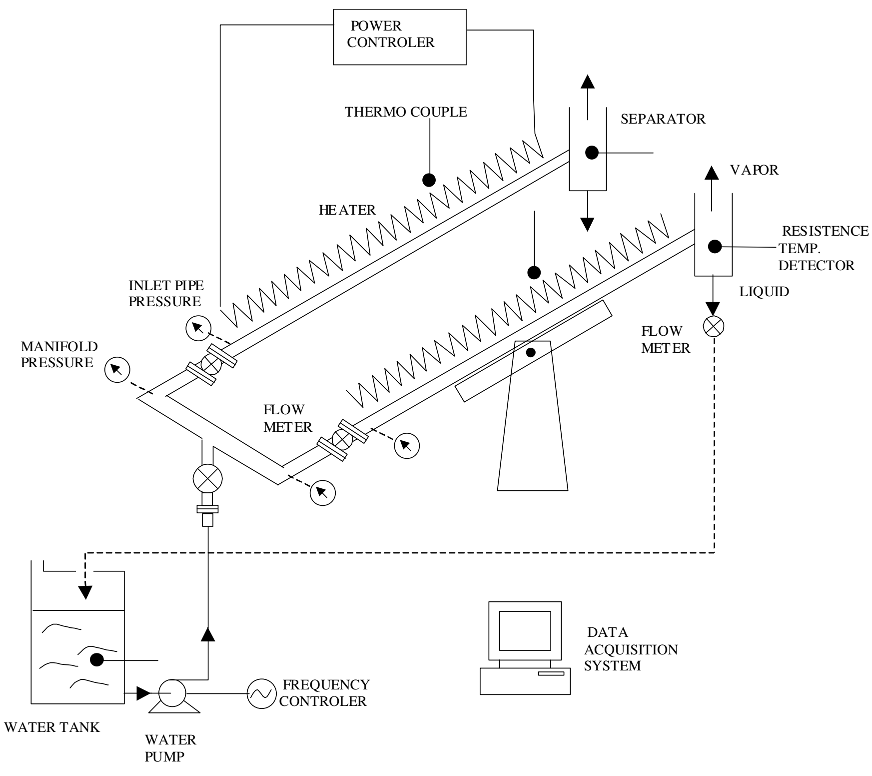


Fig. 1. Schematic experimental apparatus.

pressure gages calibrated to measure 0 to 4 bar (± 0.004 bar). The exit temperature is measured using a RTD detector (± 3 °C). The data are digitized and stored in a computerized acquisition system.

## 3. Analysis

Fig. 2 presents schematically the geometry involved. Two pipes are placed in parallel and have a common input manifold and a common output manifold. Subcooled water enters the input manifold and the flow splits into the two parallel pipes. Heating and evaporation takes place in the two pipes. Water can exit the outlet as hot liquid, liquid–vapor mixture or superheated vapor, depending on the flow rate and the heating power. It is assumed that the liquid input, $W_{in}$, and the pressure at the outlet, $P_{out}$, are known and the impinging heat along the pipe, $Q_{im}$, is prescribed. Obviously, the pressure drop for the two parallel pipes should be the same. Natan et al. (2003) developed a model for the prediction of the splitting characteristics of the flow rates in the two parallel pipes, the variation of properties along each pipe and the exit conditions.

The first step of the analysis considers a single pipe with a given input flow rate and outlet pressure. The pipe is subdivided into $I = 1, \ldots, N$ elements (see Fig. 2). Energy and momentum balances applied on each element allows the calculation of the outlet conditions based on the inlet conditions for each element (pressure, $P_i$, and enthalpy, $H_i$). Thus, if inlet flow rate, pressure and enthalpy are known it is possible to step forward and calculate the conditions from the first element to the last exit element $N$. The heat input per unit length impinging on the pipe for each element, $Q_{im}(I)$, is considered known. Yet the heat absorbed by each element, $Q(I)$, is calculated via a model that simulates the DSG process (The model is described in Natan (2000) and Natan et al. (2003)). Pressure drop in each heated element is calculated based on the local flow pattern (stratified, slug, bubble or annular flows). Using this procedure, outlet conditions (pressure, temperature and quality) are calculated based on inlet conditions. However, since we consider outlet pressure as input, iteration is performed on the inlet pressure to obtain the desired outlet pressure.

The next step is to consider a system of two pipes. Since the two pipes are fed from a common manifold and the fluids exit the system via a common manifold, the solution requires that the pressure drop for the two pipes is the same. The single pipe analysis allows to plot the calculated inlet pressure, $P_{in}$, vs. the flow rate, $W$, for a specified outlet pressure and a given heat flux. Fig. 3 shows schematic results for $P_{in}$ vs. $W$ for the two pipes, referred as the Right pipe and the Left pipe. For a given inlet pressure (given pressure drop) we may have three possible flow rates for the

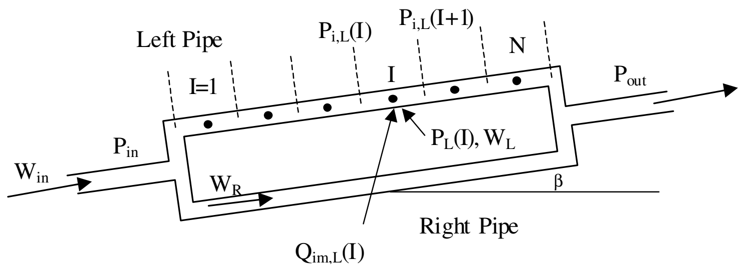


Fig. 2. Schematic flow configuration.

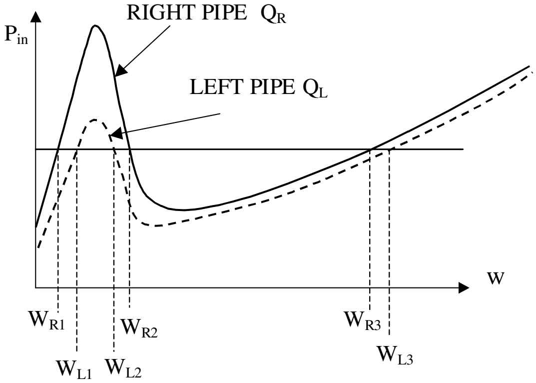


Fig. 3. Schematic inlet pressure variation for the two pipes.

right pipe ($W_{R1}$, $W_{R2}$ and $W_{R3}$) as well as 3 for the left pipe ($W_{L1}$, $W_{L2}$ and $W_{L3}$). Thus nine possible steady state solutions for the total inlet flow rate at this particular pressure is obtained, namely

$$W_{in} = W_{Ri} + W_{Lj} \qquad i = 1, \ldots, 3, \ j = 1, \ldots, 3 \tag{1}$$

Scanning pressure from low inlet pressure to high pressures yields all possible solutions for the inlet pressure and the splitting ratio $R\ (= W_{Ri}/W_{in})$ as a function of the total flow rate. For more details on the analysis see Natan (2000) and Natan et al. (2003).

Whenever multiple solutions are obtained one has to check for the stability of the steady state solutions in order to determine the actual one that will exist in reality. In the present work we follow the analysis of Akagawa et al. (1971). They showed that a system of evaporating flow in two parallel pipes is stable provided:

$$m_1(\alpha_2 - \alpha_{in}) + m_2(\alpha_1 - \alpha_{in}) \geqslant 0 \tag{2}$$

$$(\alpha_1 + \alpha_2)\left(\frac{\alpha_1\alpha_2}{\alpha_1 + \alpha_2} - \alpha_{in}\right) \geqslant 0 \tag{3}$$

where $\alpha_1$ and $\alpha_2$ are the slopes of the inlet pressure vs. the flow rate curve for each pipe (pipe characteristics) while $\alpha_{in}$ is the slope of the external inlet pressure vs. the total flow rate that enters the inlet manifold (external system or pump characteristics). m is the mass in each pipe.

For the case of a constant inlet flow rate, which is the case for the present experimental system, $\alpha_{in} \to -\infty$. Thus condition (2) is always satisfied and condition (3) is satisfied provided $\alpha_1 + \alpha_2 \geqslant 0$. Note that $\alpha_1$ and $\alpha_2$ are the slopes, at the steady state solution, of the $P_{in}$ vs. $W$ curves for the right pipe and the left pipe respectively (Fig. 3).

## 4. Experimental results

### *4.1. Single pipe*

In the first step the characteristic behavior of a single heated pipe is considered.

Fig. 4 shows the experimental results for the manifold pressure and for the pressure at the pipe inlet (see Fig. 1) for the case of impinging heat of 7.2 kW (1200 W/m) and inlet temperature of 30 °C. Likewise the respective calculated pressure curves are plotted using Natan et al. (2003) simulation for the present experimental conditions. The calculated inlet manifold pressure for an unheated pipe in which the inlet temperature remains constant is also shown.

The gray line is the calculated exit temperature for the heated pipe. For high flow rates the water which enters the pipe at 30 °C exits as subcooled liquid and the temperature is below the boiling temperature. For lower flow rates the water exit the pipe in the form of two-phase mixture with a constant equilibrium temperature of 100 °C. Further decrease of the flow rate yields superheated vapor at the pipe exit with a dramatic increase of the outlet temperature.

The experimental results for the inlet manifold pressure and for the inlet pipe pressure (the difference is the pressure drop in the flowmeter) match quite well the theoretical calculations. It is interesting to observe that the double picks of the pressure calculated at the region of low flow rates are confirmed by the experimental results. This double pick is typical of the conditions of the present experiment, namely a small diameter pipe and a high heating power. The sharp increase of the inlet pressure at low flow rates is attributed to the high velocity of the superheated steam as its temperature risers dramatically. Note that for pipes of larger diameter only one pick is calculated as shown schematically in Fig. 3 (see also Fig. 12).

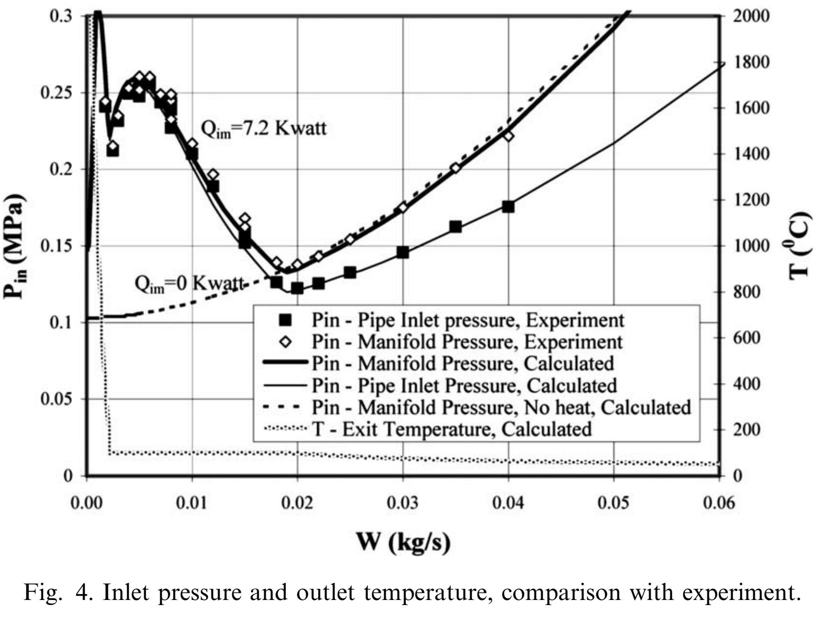


Fig. 4. Inlet pressure and outlet temperature, comparison with experiment.

### 4.2. Two pipes

Figs. 5 and 6 present the experimental results as well as the theoretical results for the splitting ratio $R$ and the inlet pressure $P_{in}$. The case where only one pipe is heated is shown in Fig. 5 while the case of symmetric heating is shown in Fig. 6. The solid lines present the theoretical steady state solutions based on Natan et al. (2003) simulation. The black lines are the solutions for the splitting ration, $R$, and the gray lines are the solutions for the corresponding inlet pressure, $P_{in}$.

As can be observed the theoretical solutions indicate that for low and high flow rates only a single steady state solution is possible. For intermediate flow rates one may obtain 3 or 5 possible steady state solutions for the splitting ratio, $R$. The thick sections of the curves of $R$ and $P_{in}$ are the regions which are unstable according to the criterion $\alpha_1 + \alpha_2 \geqslant 0$ (based on Eqs. (2) and (3)).

Fig. 5 presents the results for the case where only the right pipe is heated. For low flow rates we observe a single solution which indicates that most of the liquid prefer to flow in the unheated pipe while a very low flow rate takes place in the heated pipe. This is an unfavorable situation and one that should be considered carefully in the design of a practical solar system. In the range of $W_{in} = 0.037$–$0.05$ kg/s three theoretical steady state solutions are obtained with two stable solutions and one unstable solution. For $W_{in} > 0.05$ kg/s only a single symmetric solution is obtained, typical of high flow rates without evaporation. The purpose of the experiment is to obtain data and verify the steady state model and the approximate stability analysis.

The symbols represent the experimental steady state results. As can be seen, the data obtained compare quite well with the theoretical stable solutions. It verifies that the approximate stability analysis is applicable and no steady state data can be obtained along the thick lines. The process of obtaining the steady state data can be performed by increasing or decreasing the inlet flow rate, $W_{in}$. The circular symbols present data that are obtained while decreasing the flow rate while the

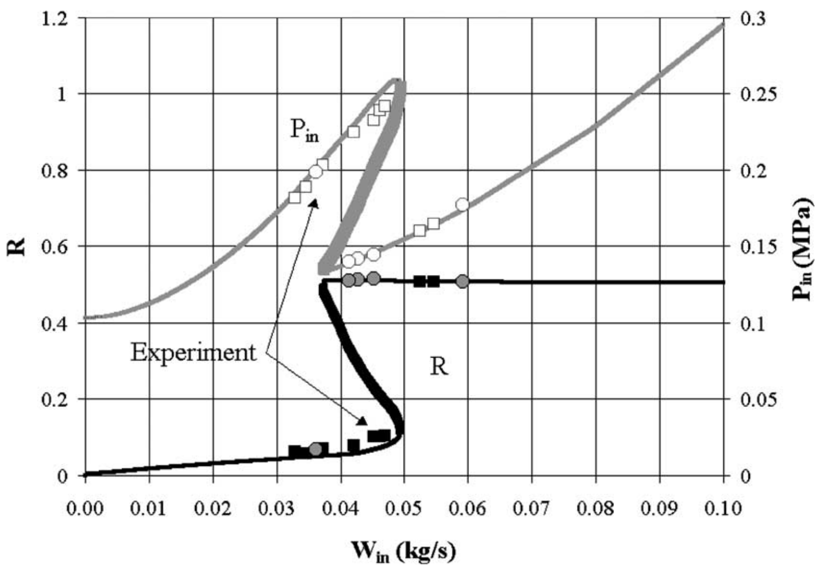


Fig. 5. Splitting ratio and Inlet pressure, right pipe 1200 [W/m], left pipe 0 [W/m].

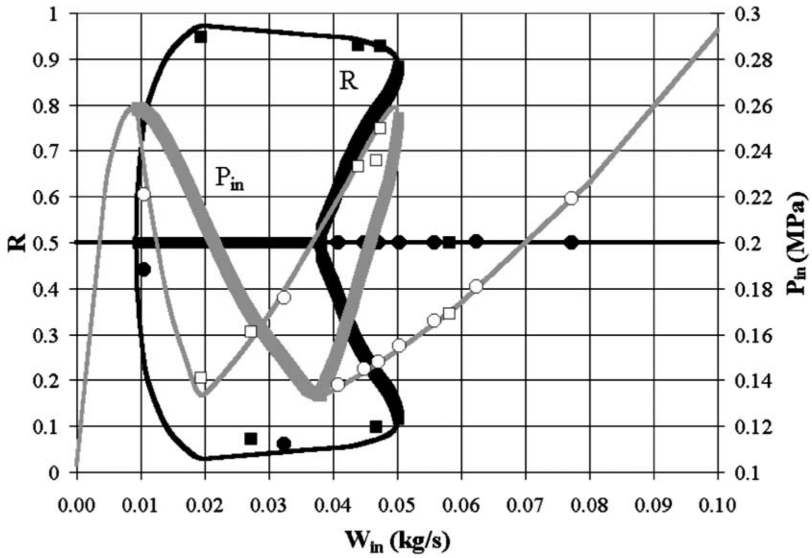


Fig. 6. Splitting ratio and Inlet pressure, right pipe 1200 [W/m], left pipe 1200 [W/m].

square symbols present the data for increasing the flow rate. In the range of $0.037 < W_{in} < 0.05$ kg/s two stable theoretical solutions are obtained, one a symmetric splitting and one where most of the flow is in the unheated pipe. The solution obtained in practice depends on the direction of the process, resulting in a hysteresis phenomenon.

The case of symmetric heating is somewhat more complex. Fig. 6 shows that for $W_{in} < 0.01$ and $W_{in} > 0.05$ kg/s a single symmetric solution is obtained. In the range of $W_{in} = 0.01$–$0.037$ kg/s the theoretical solutions for the symmetric distribution of the flow rates are unstable resulting in very low flow rate in one pipe and high flow rate in the other pipe. For $W_{in}$ ranging from 0.037 to 0.05 kg/s three stable solutions exist, a symmetric distribution of the flow rates and a solution in which most of the flow takes place in the right or the left pipe. Similarly to Fig. 5, the experimental results are shown by the circular or the square symbols depending on the way the data is obtained. It is interesting to observe that although the heating is symmetric there is a region in which the stable solution is the one where most of the flow takes place in one pipe and not the solution that results in a symmetric splitting. In addition a hysteresis phenomenon may take place also in this case.

## 5. Some design considerations for DSG systems

The experimental results that are detailed in the previous chapter indicate that the model and the stability analysis are a valid tool for designing DSG systems.

As an example for a "real" solar system we consider two parallel steel pipes, heated by solar radiation with the following parameters: Inlet temperature 25 °C, exit pressure 3 MPa, pipe length 400 m, pipe diameter 2.5 cm and inclination angle of 10°. In order to minimize heat losses to the surroundings each pipe is insulated from the surroundings by a glass tube with vacuum in the annular spacing (Fig. 7).

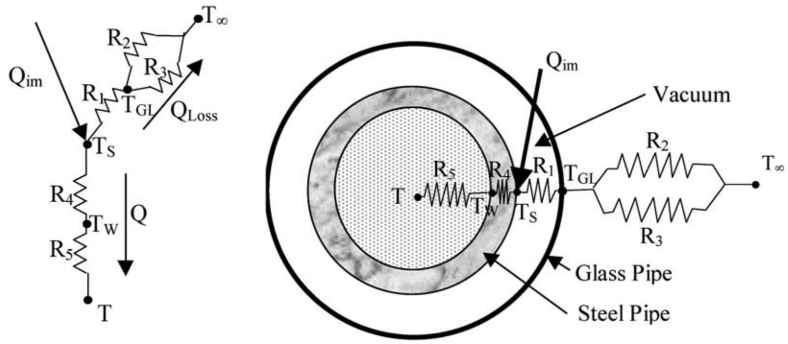


Fig. 7. The heat transfer scheme.

The radiant heat impinging on the surface of the pipe, $Q_{im}$, is considered known. The pipe external surface is assumed black. The radiant heat is absorbed on the pipe surface. Part of the heat flows into the water and part is lost to the surroundings. Electrical analog of resistances (Fig. 7) is used to calculate the flow of heat to the water, $Q$, and the heat lost to the surroundings, $Q_{Loss}$. $R_1$ is the radiation resistance through the annular vacuum. $R_2$ and $R_3$ are the convective and radiative resistances for the losses from the glass pipe surface, $T_{GL}$. $R_4$ is the conductive resistance from the steel pipe surface, $T_S$, to the inner pipe wall, $T_W$, and $R_5$ is the convective resistance between $T_W$ and the water, $T$. The calculation procedure is detailed in Natan et al. (2003).

Fig. 8 presents typical results for symmetric heating, namely each pipe is heated with impinging radiant energy of 1200 W/m. The black line is the splitting ratio, $R = W_R/W_{in}$. It shows that for low inlet flow rates there is only one solution, likewise for high flow rates. For intermediate flow rates we may have 3 or 5 possible steady state solutions. The brown line in Fig. 8 shows the inlet

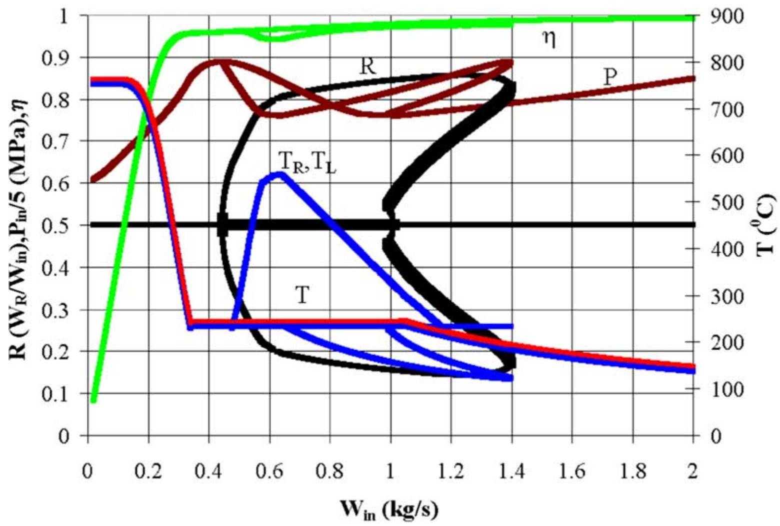


Fig. 8. Splitting ratio, inlet pressure, temperatures and thermal efficiency case: right pipe 1200 [W/m], left pipe 1200 [W/m].

pressure for the various solutions. Since the heating is symmetric we obtain two inlet pressures for the case of 3 splitting solutions and 3 for the case of 5 solutions. The thick black lines show the unstable steady state solutions for the splitting ratio. Note that the unstable solutions are not shown on the other curves.

The red line presents the mixture temperature at the manifold exit. For high flow rates the water is still subcooled and its temperature decreases with the increase of the flow rate. For intermediate flow rates the water at the manifold exit is in the form of a two phase mixture and the temperature is constant and equal to the equilibrium mixture temperature at 3 MPa ($T = 234$ °C). For low flow rates superheated steam exit the system. The mixture temperature increases quit rapidly with the decrease of the flow rate. Eventually it reaches a theoretical limit of 750 °C. At this temperature the impinging heat is completely lost to the surrounding and none is absorbed by the steam. Obviously in practice care should be taken to avoid such extreme temperatures. It is interesting to observe that in the region where multiple solutions are obtained ($W_{in} = 0.43$–1.4 kg/s) the mixture temperature at the outlet is practically the same for the different solutions. Obviously for the case of symmetric flow (high and low flow rates) the temperatures in both pipes are the same and they are equal to the mixture temperature.

In contrast to the red line which represent the exit mixture temperature the blue line shows the exit temperature for each of the two pipes (before mixing). It can be observed that for the region where we have multiple solutions the temperature at the exit of one pipe can be considerably different than the temperature of the other pipe. This occurs when most of the flow takes place in one pipe.

The green line in Fig. 8 presents the thermal efficiency of the heating process, namely the ratio of the heat that enters the water divided by the total impinging radiant heat. As can be seen for high and intermediate flow rates the efficiency is very high. This is due to the very effective insulation that minimizes the losses to the surrounding. On the other hand, for low flow rates, the steam temperature is very high, the losses are increased and the efficiency drops quite rapidly.

Two basic design methods for the evaporation process can be considered. The once through operation, Fig. 9a, in which case superheated steam flows out of the piping system directly to the turbine, and a recirculation method, Fig. 9b, in which heating is performed in two stages, evaporation and superheating.

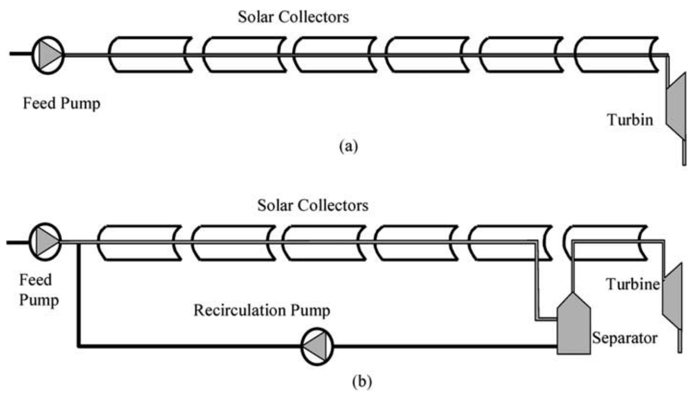


Fig. 9. Basic DSG processes: (a) once-through and (b) recirculation.

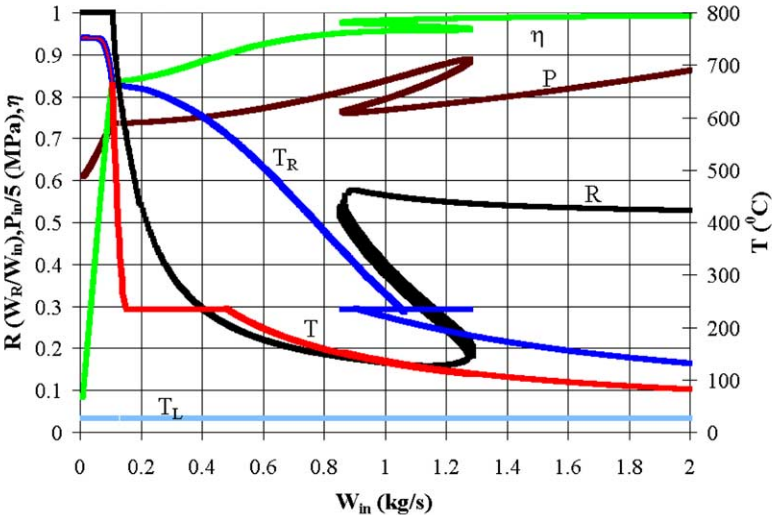


Fig. 10. Splitting ratio, inlet pressure, temperatures and thermal efficiency case: right pipe 1200 [W/m], left pipe 0 [W/m].

For both methods Fig. 8 can provide considerable insight. For the once through method, Fig. 8 shows that in order to get superheated steam from the outlet manifold, the inlet flow rate should be less than 0.35 kg/s. Thus, we are at a region of a single solution of even splitting. Within this region, it is desired to obtain high temperature, yet high temperature causes a decrease of the efficiency. An optimum design should be a compromise between the desire for high temperature and high efficiency (around 0.2 kg/s).

For the case of the recirculation type the exit to the separator is in the two-phase region. Thus the flow rate can vary from 0.35 to 1 kg/s. In most of this region, even splitting is not stable, and the practical situation is that the flow rate in one pipe is very low (about 15%). Thus although the outlet mixed temperature is a low equilibrium temperature one has to be aware (while designing the system) of the high temperature that can exist in one of the pipes (Fig. 8).

Fig. 10 presents the case where only the right pipe is heated while no heat is provided to the left pipe. Obviously this is not a desired operation but one that can occur when one line looses its focus or the line is temporarily in the shade due to local cloud cover. The black line presents the splitting characteristics of the flow rates. For low flow rates most of the liquid tend to flow in the right (heated) pipe. But, as the inlet flow rate increases, the flow rate in the heated pipe decreases to about 15% of the total flow rate. Note that in the region where the mixture temperature at the exit is relatively low the temperature in the heated pipe may be quite high ($T_R$).

Fig. 11 presents the same information for impinging radiation of 1200 W/m for the right pipe (as before) and reduced power of 900 W/m for the left pipe. As can be observed the situation is quite complex. For flow rates less than 0.55 kg/s and higher than 1.4 kg/s we have a single solution. The once through method can take place for $W_{in} < 0.3$ kg/s in which case the steam at the exit is superheated. Since the purpose is to obtain high temperature as well as high efficiency the recommended inlet flow rate should be around 0.2 kg/s. Note that the flow rate in this region is approximately symmetric and the mixture temperature (the red line) is in between the right pipe

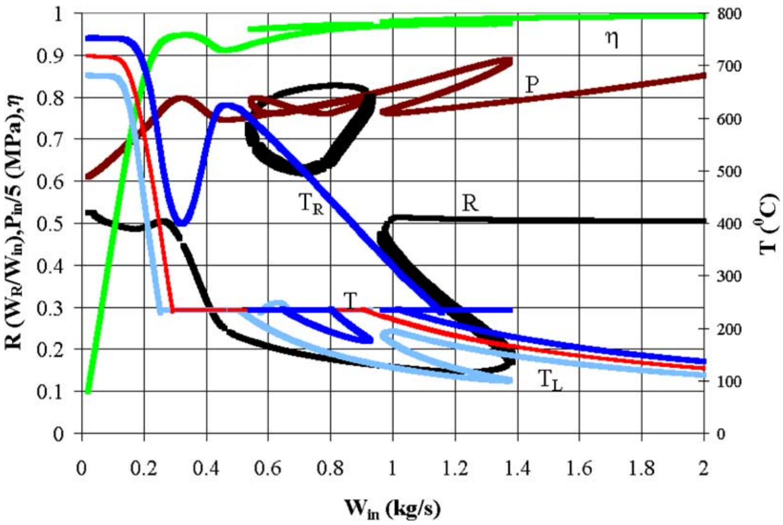


Fig. 11. Splitting ratio, inlet pressure, temperatures and thermal efficiency case: right pipe 1200 [W/m], left pipe 900 [W/m].

exit temperature, the blue line, and the left pipe exit temperature, the light blue line. For higher input flow rates ($W_{in} > 0.3$ kg/s), the water at the manifold exit is in the form of liquid–vapor mixture. The flow rate in the right heated pipe reduces, causing a high temperature of the steam in this pipe and one should make sure that the piping system are designed for this high temperature.

The effect of the inclination angle is shown in Fig. 12. In this figure the single pipe performance is plotted vs. inclination angle for 1200 W/m. It is interesting to observe that for angles larger than

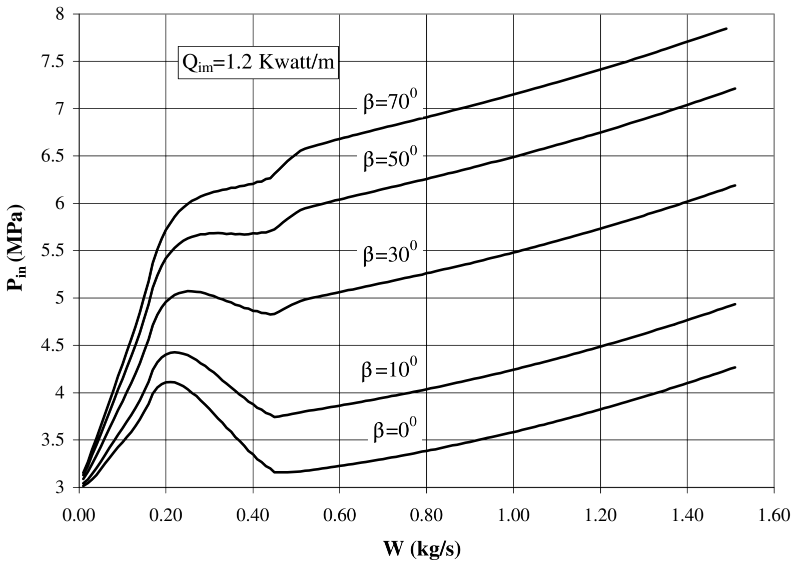


Fig. 12. Effect of inclination on a single pipe performance.

50° the curve of $P_{in}$ vs. $W$ becomes a monotonic increasing line. In this case we should not expect any problems related to multiple solutions that are anticipated when the derivative of $P_{in}$ vs. $W$ is negative. Obviously for most power stations where the parallel lines are vertical, operational problems such as mentioned in this paper may be absent.

## 6. Summary and conclusions

An experimental system consisting of two parallel pipes with a common inlet manifold has been constructed. Water at room temperature enters the inlet manifold and splits into the two pipes that are electrically heated. Water can exit the pipes in the form of subcooled liquid, gas-liquid mixture or superheated steam, depending on the flow rate and heating power.

The main purpose of this work is to check experimentally the validity of the theoretical simulation presented by Natan et al. (2003) and to determine the actual physical solution whenever multiple steady state solutions are obtained theoretically.

Two extreme cases are chosen (1) the case where only one pipe is heated. (2) The case of even heating of both pipes. The obtained data compares quite well with the theoretical analysis. An absence of experimental data along the theoretical unstable branch is observed. On the other hand the data agrees well with the theoretical stable solutions. In the zone of multiple stable solutions all possible solutions were practically obtained and the actual solution depend on the direction leading to the steady state (hysteresis phenomenon).

The theoretical model is further used to analyze a ‘‘real’’ DSG system with application to design parameters such as splitting ratio of the flow rates, inlet pressure, thermal efficiency, mixture exit temperature and the exit temperature of each pipe. Practical design considerations for the once through and recirculation systems are included.

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