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STUDIES OF THE FLOW IN THE LINER OF A GEOTHERMAL WELL

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ABSTRACT

This paper reports part of an ongoing program to study the flow in a geothermal well. In this paper we look at the fluid processes that occur in the liner of the well and are particularly interested in the pressure losses that are associated with the slotted (perforated) liner. A data bank of well measurements has been analysed to give a representative value of the liner roughness and a laboratory experiment was built to investigate the complex nature of the flow in the liner and annulus. Finally a computer simulation was developed which allowed an investigation of the effect of some of the variables on the fluid flow. These studies are reported together with some discussion and recommendations of values for liner roughness to use in wellbore simulations.

INTRODUCTION

A geothermal well contains a casing string. This will include a production casing cemented to some competent formation just above the known reservoir. After drilling the length of the reservoir most wells will include a length of slotted (perforated) casing which is known as the liner which extends between the production casing shoe and the bottom of the well. Its function is to provide a clear passage for the reservoir fluid to enter the production casing and hence find its way to the surface. Some wells are left open below the casing shoe when "caving" is thought to be unlikely or the length of the open hole is relatively short. In this study we looked at wells with liners.

There are many variables which can control the flow of fluid in the well. A well can contain several feed zones located at different depth intervals supplying fluid at different pressures and enthalpies. Fluid from these feed zones may flow radially into the liner or up (or down) the annulus between the open hole and the liner. The annulus and the slots could be obstructed by caving or deposition of calcite or silica. The slots or perforations usually have very rough surfaces causing high pressure losses. If the fluid is two phase in the liner the uncertainties increase.

Studies of fluid flow in a well must therefore include the slotted liner. The liner is not cemented to the formation, it either hangs under tension if anchored at the casing shoe or rests loosely on the bottom of the well. It could be slotted along all its length or only near permeable zones. There are also different shapes and sizes of the holes in the liner, some are rectangular which we have called slots, others may be circular (perforated).

When the fluid entering the liner at the feed zones is liquid and flashing occurs in the production casing above the liner, the pressure drop in the liner is usually dominated by gravity and detailing the flow in the liner may not be very important. However if the fluid in the liner is steam or two phase, then frictional losses become important. It is then necessary to be able to calculate the frictional losses in this part of the well. Gould(1974) reported that his calculated pressure drops were sensitive to the roughness values assumed for the slotted liner. He suggested a value of $1.37*10^{-4}$ m. This number was also used by Catigtig(1983).

For this study we analysed our data bank to obtain a representative value of the liner roughness. Also we designed an experiment to study the flow in the liner and annulus and finally a computer simulation of the flows was attempted to look at the effect on the flow distribution when some of the key variables were changed. This paper reports these studies.

REVIEW OF WELL DATA

To make a comparison of the laboratory and full scale results a review of our well data bank was made. For the comparison it was decided to analyse the dynamic measurements obtained from a well and to estimate a value for the surface roughness of the liner, using the assumption that all the flow is on the inside of the liner. This is in line with the current use of roughness values in most of the existing simulators.

Much of the data gathered from wells during dynamic tests have been found incomplete. This can be partly attributed to the difficulties in performing the tests. The required set of data for the analysis was:

- wells with slotted/perforated liner
- single phase fluid in the slotted liner
- location of feed zones
- dynamic temperature and pressure measurements
- well geometry
- mass flow rate
- enthalpy
- dissolved solids and gases

Wells with insufficient information were excluded from the analysis. In the case of multiple feed wells the flow rate measured at the surface is cumulative. It was thus found appropriate to concentrate on the length of the slotted liner above the shallowest feed zone. Also many of the wells in the data bank are from liquid dominated fields, so we have only used wells with flashing zones above the area of interest. The steps followed to evaluate a representative roughness value are given below.

Neglecting acceleration pressure gradient.

$$(dp/dz)_{total} = (dp/dz)_{friction} + (dp/dz)_{gravity}$$

$$(dp/dz)_{gravity} = rho_{av}.g.Sin0$$

$$(dp/dz)_{friction} = (dp/dz)_{total} - (dp/dz)_{gravity}$$

$$(dp/dz)_{friction} = f' \, rho_{av}.V^2/2\,Di.$$

Where f' = friction factor assuming all the flow is in the liner.

Di=inside diameter of the liner

rho_{av} = average density which is a function of the average temperature

V = total mass flow/(rho_{av}.π.(Di^2/4))

(e/D) = relative roughness which is a function of Reynolds Number and the friction factor is obtained from the Moody diagram.

$$e_{total} = (e/D)\,Di$$

Where e_{total} = roughness assuming all the flow is inside the liner.

Tabulated values, Table 1, show that the range of roughness values for the well selected is within two orders of magnitude. All the values lie in the range $1.1*10^{-4}$ m to $1.5*10^{-2}$ m. A statistical analysis was done on the data. The value of $1.5*10^{-2}$ m was eliminated since it was found outside an acceptable deviation. Analysis of the rest of the data gives a mean of $4.3*10^{-3}$ m with a standard deviation of 3.9. The high value of the standard deviation shows the diversity of the roughness values. Roughness values in the range $1.0*10^{-3}$ m to $7.0*10^{-3}$ have a high probability with respect to the mean. Accuracy of the data acquisition system is very important for this exercise. Slight errors in measurement or reading of gauge charts leads to unacceptable values of roughness. What is needed is a series of designed downhole experiments to detail with high accuracy the roughness values under controlled conditions.

EXPERIMENTAL WORK

In order to obtain a better understanding of the flow in the slotted liner a theoretical study, described in the next section, and an experimental study was undertaken. In general, production geothermal flows in the liner will be turbulent, also many wells use a geometry which have a liner 1" smaller in diameter than the open hole, eg 8" open hole diameter with 7" liner. It is also well known that liners may not be set concentric in the hole and open hole diameters may not remain constant throughout the length due to caving etc, within the formations. Many geothermal wells contain liners with slots with a geometry of 50mm * 20mm slots at 52 slots per metre. Some liners are perforated instead of slotted using a drilling (boring) machine. It was important therefore that the experimental rig should allow identification of the flow distribution in the duct and to supply information on the effects of the slots on the pipe roughness. The test rig was designed with the above considerations in mind.

A 50.8mm(2") diameter PVC pipe for the liner with a 76.2mm(3") pipe representing the open hole were selected. The 76.2mm(3") pipe was constructed with an Acrylic section which allowed flow visualisation. Air was the working fluid so gravity was not important and the rig was built horizontal. The PVC liner was perforated with 20mm holes at 50 holes per metre. The total length of the rig was 5.4m and the inner pipe was centralised along its length by supports. Air is fed radially into one end by four 25.4mm(1") hoses connected to the air supply. At the exit from the duct the annulus was blocked to represent the production casing shoe. The maximum airflow rate was 0.25kg/s at a pressure of 41kPa gauge.

Instrumentation included wall pressure tappings along the length and around the circumference of the outer and on the inner wall of the annulus at selected points. Pressure measurements were taken on a multitube manometer open to atmosphere at one end. An orifice plate manufactured to BS 1042 and fitted upstream of the rig was used to monitor massflow rate with upstream pressure, temperature and relative humidity recorded in order to calculate rig air density. To obtain the flow distribution a small diameter pitot static tube was traversed across the annulus and halfway across the inner tube(liner) at selected positions.

EXPERIMENTAL RESULTS

The pressure gradients are illustrated on Figure 1 for different flow rates. For most of the length of the duct the gradient is constant as might have been expected, indicating a simple relationship between length and pressure drop. However the pressures on the outer and inner wall of the annulus are equal, apart from the two ends, indicating no mass transfer radially along the length. At the ends flow enters and leaves the annulus, the effective length being about 14 diameters.

Three positions were selected for the flow distribution analysis, .35m, 1.78m, and 3.5m from the inlet. The velocity profiles were then analysed to give the mass flow rates in each duct, ie the liner and the annulus.

The gradient and flow distribution measurements were then used to obtain some characteristic duct roughness values for the inner pipe and annulus. Assumptions made were :

1) One Dimensional steady horizontal flow

2) Only frictional pressure drop is of importance

As seen from the pressure gradient results the flow stabilises after a short distance from the inlet, this was also confirmed by the flow distribution measurements. The analysis was therefore done using the pressure gradient calculated for the centre section of the duct and the flow measurements taken at the station 3.5m from the inlet. The mean velocity and mass flow were calculated from the velocity profiles. Using a representative pressure gradient and the mass flow, Reynolds numbers and friction factor were calculated and estimates of equivalent roughness values, as given by the Moody diagram, were made for the inner duct and annulus. The resulting values are given in Table 2. The experimental pipes are PVC and Acrylic and have smooth walls. The effect of the perforations is to increase e_{inner} and e_{outer} to $8*10^{-4}$m and $3.5*10^{-5}$m respectively. The annulus consists for the experiment, of a smooth outer wall and a perforated inner wall giving a lower roughness than the inner pipe.

FLOW SIMULATION

Assuming a steady one dimensional flow the equations for pressure gradient in horizontal flow are :

For inner pipe

$$dp_1/dx = rho\ f_1 . V_1^2/2.D_1$$

and for the annulus

$$dp_2/dx = rho\ f_2\ V_2^2/2.D_2$$

The relationships for mass transfer between the annulus and the inner pipe used were:

$$dM_1/dx = \alpha.(p_2 - p_1)^{5}$$

$$dM_2/dx = -\alpha.(p_2 - p_1)^{.5}$$

where α is a flow coefficient which is a function of, amongst other things, the area of the perforations. A simultaneous solution of these equations will give the flow distribution between the annulus and liner and the corresponding pressure gradients.

To solve the non linear ordinary differential equations a computer program was developed coupled to DO2RAF, a NAG Fortran library routine. Boundary values have to be supplied and in our case we chose to use the inlet total mass flow rate and the exit pressure of the inner duct(liner). The solution is computed using a finite difference technique with deferred correction connected to a Newton iteration to solve the finite difference equations. The Newton iteration uses Jacobian matrices. The method requires an absolute error tolerance and an initial mesh and approximate solution. The approximate solution is corrected using Newton iteration and deferred correction. If a solution is not obtained with the initial mesh, additional points are added to the mesh and the solution is recomputed until the error everywhere is within the specified tolerance. The error is approximately distributed equally on the final mesh.The solution is displayed on the final mesh.

USE OF THE PROGRAM.

The program was first run with input values from the laboratory experiment,including the roughness values determined as explained above. Fluid properties were assumed constant and initial values for the unknown pressures were taken to be the measured exit pressure in the inner pipe. A small value was first selected for α and resulted in unstablised flow throughout the ducts. It was then increased until a stable flow was obtained in the central part of the duct.

The input data for stable flow was:

Inner pipe I.D.	0.032m
Inner pipe O.D.	0.060m
Outer pipe I.D.	0.078m
Inner pipe roughness	$8*10^{-4}$m
Annulus roughness	$3.5*10^{-5}$m
Duct Length	5.4m
Initial mesh points	151
Flow coefficient α	0.016

The simulated and experimentally determined pressure and flow distribution are illustrated in figures 2 and 3. The simulated results are in good agreement with the experiment. At inlet, pressures in the annulus are higher than in the liner so fluid flows radially into the inner pipe. At about 0.7m from the inlet (14*I.D.of inner pipe) the pressures between inner and outer equalise and the mass transfer stops. The mass flows in each of the passages remain constant until the exit zone which occurs at about the same distance from the exit, when the process is repeated with mass being transferred from the annulus to the inner pipe. The simulated results show that there is no massflow from the inner pipe to the annulus.

The method and assumptions used for the simulation are assumed to be validated by the experimental results. We then studied using the computer program the sensitivity of the distribution of flow between annulus and liner to changes in some of the parameters . It can be shown that the ratio of mass flows is a function of the flow areas, inner diameter and annulus hydraulic diameter the inner and equivalent annulus roughnesses and the respective Reynolds number. For this exercise we used data as below and allowed the well to be vertical so that both friction and gravity were included.A 10 m length was chosen and steam, liquid and two phase fluid in the liner and annulus were analysed. The roughness values used were those obtained from the laboratory experiment and a fluid temperature of 250°C was selected with fluid properties assumed constant over the 10m length. Two mass flows rates were chosen 10 and 50 kg/s.

e_{inner} = $8*10^{-4}$m

$e_{annulus}$ = $3.5*10^{-5}$m

Liner I.D. = 0.15m

Liner O.D. = 0.1683m ($6^{5}/8$")

Well I.D. = 0.1937m ($7^{5}/8$")

A selection of the results is shown in figures 4 to 7.Figures 4 and 5 show the dependence of frictional pressure drop on the roughness of the inner pipe(e_1). As is shown the pressure gradient is highly sensitive to the value of e_1. The dependence of flow distribution in the inner pipe and annulus on the total mass flow and on e_1 is shown in figure 6. As with the pressure gradient the flow is sensitive to e_1. However it is not as sensitive to total mass flow. This is because for constant flow geometry and duct roughness the mass ratio depends on Reynolds number (a function of total mass) which loses its importance at very high Reynolds numbers. Figure 7 shows the effect of varying duct roughness on the roughness obtained by assuming all the flow is in the inner pipe (e_{total}). As is shown, for the set of data used the selection of e_1 is more important than e_2. This is due to the larger proportion of flow in the inner pipe.

CONCLUSION

Determination of liner roughness values from well data requires high quality measurements and careful selection if meaningful results are to be obtained.Analysis of our data bank gave values over two orders of magnitude. However we would recommend that a reasonable roughness height for a liner would be in the range $1*10^{-3}$ to $7*10^{-3}$ metres.This compares with that used by Gould(1974) of $1.37*10^{-4}$m.

Laboratory experimental results

validated the computer simulation. They showed that the pressure gradient was constant in the central part of the duct away from the ends. The measurements also showed that there was no mass transfer in this section, mass transfer from annulus to inner pipe only occurred at the two ends, there was no indication of flow from inner to annulus.

The experiment used PVC and Acrylic pipes which are considered smooth. The high roughness values obtained, $8*10^{-4}$ and $3.5*10^{-5}$ metres, is attributed to the perforations.

The computer program allowed a study to be made of the sensitivity of a liner performance to variation in a number of parameters.

ACKNOWLEDGEMENTS

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REFERENCE

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Catigtig, D.C. 1983, Boreflow Simulation and its Application to Geothermal Well Analysis and Reservoir Assessment, UNU Geothermal Training Programme, Iceland, Report 1983-8

TABLE 1 Roughness Values for selected wells

No	Field	Well	Mass kg/s	Liner Dia(m)	$(dp/d_z)_{tot}$ (Pa/m)	Temp oC	f' (m)	e_{total}	Remarks
1	Wairakei	207	9.72	0.1504	8100	238-240	0.086	$11*10^{-3}$	
2.	Broadlands	23	40.8	0.1504	8508	260	0.037	$1.4*10^{-3}$	
3	Broadlands	27	10.28	0.1504	7674	264	0.08	$9.6*10^{-3}$	
4	Kawerau	27	60.83	0.1504	8575	262	0.018	$.11*10^{-3}$	
5	Yangbajing	327	21.39	0.2245	9000	152	0.031	$1.2*10^{-3}$	Shallow
6	Yangbajing	328	32.78	0.2245	9080	156	0.083	$15*10^{-3}$	Shallow
7	Tongonan	105D	12.0	0.1594	7425	266-267	0.052	$3.7*10^{-3}$	Deviated
8	Tongonan	106	13.5	0.1594	7600	272	0.054	$4.3*10^{-3}$	
9	Tongonan	1R3	13.0	0.1594	7667	270	0.078	$9.5*10^{-3}$	
10	Tongonan	409	22.0	0.1594	7200	296	0.025	$0.43*10^{-3}$	
11	Tongonan	MB2	10.6	0.1594	7617	266	0.019	$0.13*10^{-3}$	
12	Tongonan	MB9	19.7	0.1594	7900	255	0.007	$1.1*10^{-3}$	
13	Tongonan	1R5D	8.7	0.1594	7750	247	0.077	$9.6*10^{-3}$	Deviated
14	Tongonan	2R3D	35.0	0.1594	8000	264	0.061	$5.3*10^{-3}$	Deviated
15	Tongonan	2R4D	20.8	0.1594	7800	260	0.045	$2.2*10^{-3}$	Deviated

TABLE 2 Experimental Results

	Run1	Run2	Run3
Total mass flowrate.(kg/s)	0.086	0.113	0.135
Inner flow at 0.35m (kg/s)	0.042	0.055	0.066
Outer flow at 0.35m (kg/s)	0.044	0.058	0.069
Inner flow at 3.5m (kg/s)	0.052	0.065	0.081
Outer flow at 3.5m (kg/s)	0.034	0.045	0.054
Stabilised press grad(Pa/m)	210	315	475
Mass Flow ratio-inner/outer at 3.5m	1.53	1.51	1.50
e_{inner} (m)	$7.90*10^{-4}$	$7.85*10^{-4}$	$7.80*10^{-4}$
e_{outer} (m)	$3.33*10^{-5}$	$3.51*10^{-5}$	$3.60*10^{-5}$

FIG.1 MEASURED PRESSURE GRADIENT -AIR FLOW

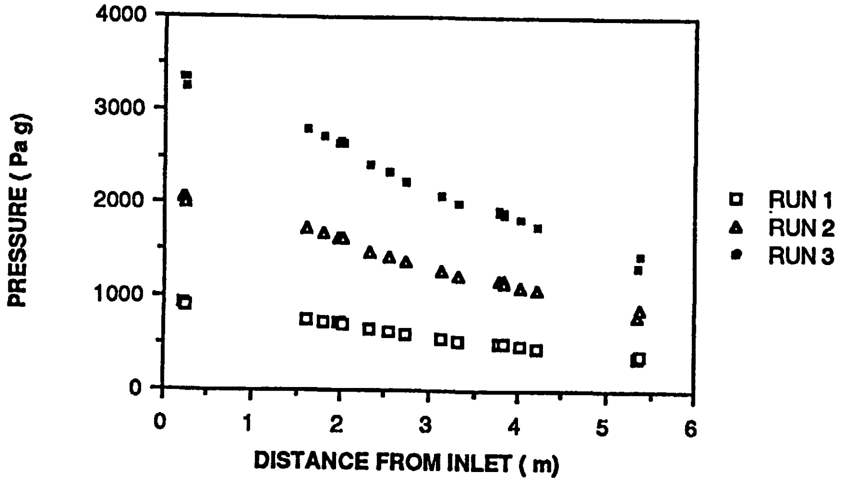


FIG.5 EFFECT OF E1 ON FRICTIONAL PRESSURE DROP
STEAM FLOW M=50 kg/s

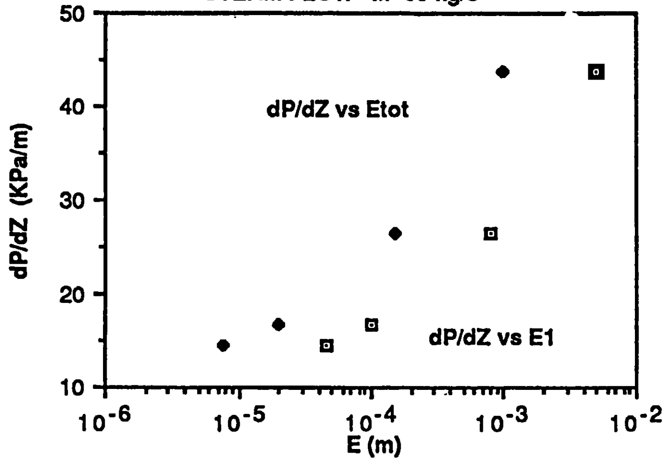


FIG.6 EFFECT OF TOTAL MASS FLOW ON FLOW DISTRIBUTION
- STEAM FLOW

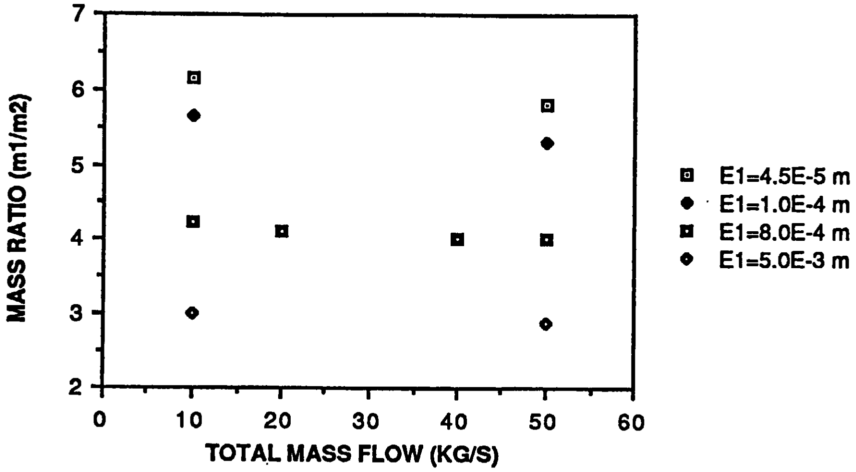
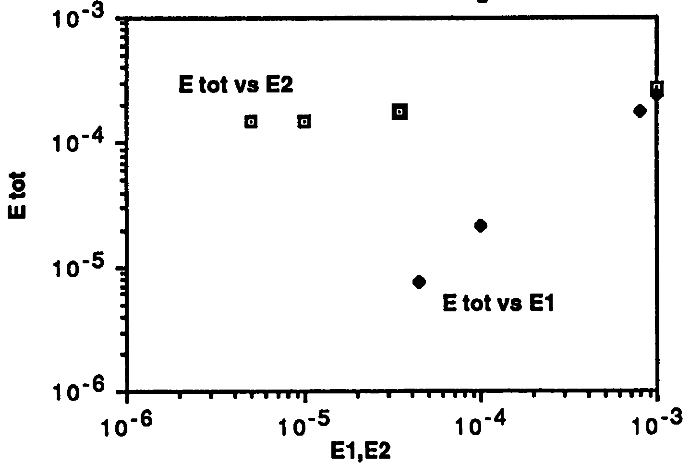


FIG.7 EFFECT OF VARYING PIPE AND ANNULUS ROUGHNESS ON E tot
-WATER FLOW M=50kg/s



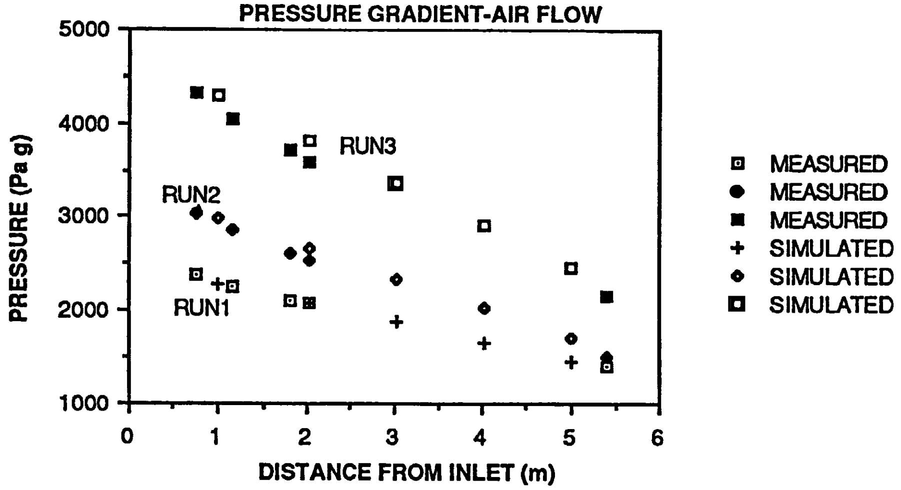


FIG.2 COMPARISON OF EXPERIMENTAL AND MEASURED PRESSURE GRADIENT-AIR FLOW

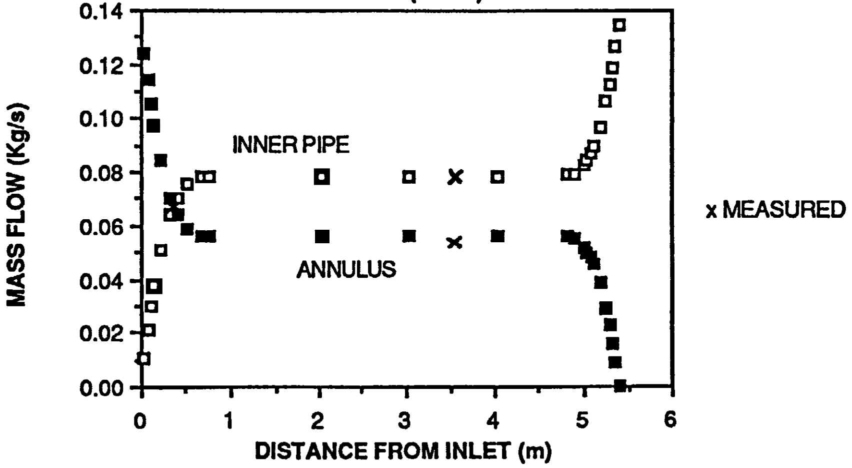


FIG.3 SIMULATED FLOW DISTRIBUTION AIR FLOW (RUN3)

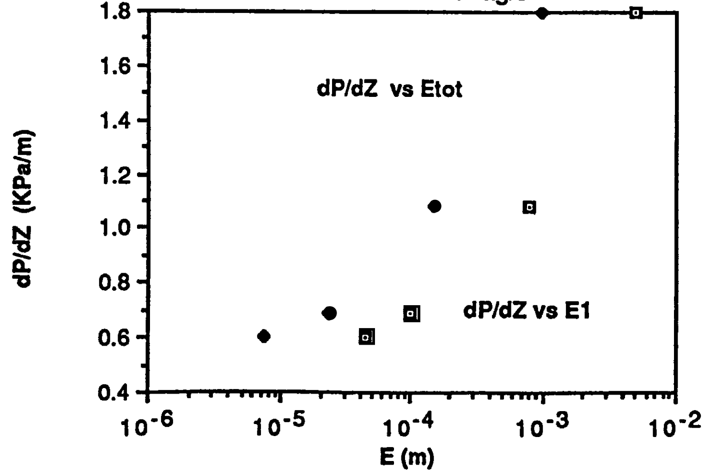


FIG.4 EFFECT OF E1 ON FRICTIONAL PRESSURE DROP STEAM FLOW M=10 kg/s