PROCEEDINGS, Twenty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 1966
SGP-TR-151

A STUDY OF THE PROPAGATION OF COMPRESSION WAVES IN POROUS MEDIUM FILLED WITH STEAM

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ABSTRACT

A preliminary investigation on the propagation of compression waves through a radial system of porous medium filled with steam has been conducted for the case of uniform and non-uniform basic temperature distributions. When a relatively weak pressure disturbance is introduced as a signal source in a uniform temperature system, it is found that the pressure disturbance decays away and smears out as time progresses. However, for the case of a non-uniform basic temperature distribution, the temperature gradient and fluid viscosity give significant effects on the reduction of pressure signal attenuation.

The attenuation of the compression waves depends on the wave frequencies. For higher frequencies the strength of the signal decays rapidly, and for lower frequencies the signal could propagate farther away. It is found also that porosity and permeability distributions gives significant effects on the amplitude and the wave profiles.

INTRODUCTION

Wave propagation has become an increasingly interesting subject to be explored since many importance theories derived from this subject have been found to be powerful tools in engineering and science especially in dynamic systems, whether in solids, liquids, or in gases.

In the field of heat transfer, fluid dynamics, and combustion, wave propagation mechanism has been found to be responsible in transferring energy in molecular scales. Theoretical works have been conducted to study the role of thermodynamical and mechanical responses arises when thermal or mechanical disturbances introduced in a compressible system. This work is meant to be an extension of some theories, originally developed in fluid dynamics and heat transfer, which might be applicable in the system of porous media.

Acoustic waves play very important roles in generating thermoacoustic convection, when heat deposition is relatively fast (Sutrisno, 1989, and Sutrisno, 1994). Furthermore, the development of acoustic waves might be capable of generating shock waves when heat addition becomes extremely fast (Sutrisno & Kassoy, 1991). An investigation of acoustic waves propagation through viscous, heat conducting gases involving momentum and heat diffusion mechanism has an application in developing an indirect measurement method for Prandtl number of gases (Sutrisno, 1991).

Pressure interference testing is essential for establishing geothermal reservoir connectivity and for determining interwell connectivity (Garg and Pritchett, 1993). In two-phase systems, because of extremely large compressibility, or correspondingly small diffusivity, it may be impractical to run an interference test in a reservoir with extensive two-phase zones. Since pressure interference signals may be quite weak, it is essential to characterize background noise to design interference tests such that signal-to-noise ratio is acceptably high.

In this preliminary work, the analytical method is used to study wave propagations in porous media filled with compressible substances, such as steam or gases. It is hoped that the results might be useful in the geothermal reservoir engineering.

This work concerns with an analytical investigation on the propagation of compression waves through porous medium filled with gas. The focus of the study is to gain the basic physical understanding of wave propagations. The model for porous system is assumed to have cylindrical geometry such that compression waves can propagate only radially. In this system, the gaseous fluid behaves as an ideal gas, and it is always in thermal equilibrium with the porous rock matrices. Fluid motion is solely governed by Darcy's law, and the buoyancy effect is neglected. It is assumed further that the rock matrices are perfectly rigid.

On a system with a uniform temperature distribution, if it is disturbed by relatively high frequency, sinusoidal compression waves, the signal decays away rapidly as it moves through the porous medium. For lower frequencies, the wave attenuation is weaker, and the waves can propagate farther distance away from the source. It is to be noted that the strength of the signal is significantly weakened as time progresses.

For a system with a non-uniform basic temperature distribution, the existing temperature gradient in the system gives an additional effect on the originally diffusive system. Further theoretical studies are necessary to characterize the dominant factors controlling signal amplifications.

MATHEMATICAL MODEL

An idealized system is considered in this analysis. A radial system of porous medium filled with steam as illustrated in Fig.1, would be subjected to a localized pressure disturbance at the center region of the system. At first, the steam is at rest in an equilibrium thermodynamic state, with possibilities that the basic temperature and density of the system vary radially.

The governing equations for the pressure wave propagation in the radial, viscous, heat conducting, compressible system can be derived from Brownell, Garg & Pritchett (1977) to yield the following governing equations. They are mass conservation, the Darcy's law and the energy conservation.

$$\phi\frac{\partial \rho'}{\partial t'}+\frac{1}{r'}\frac{\partial}{\partial r'}(r'\rho' u')=0 \qquad (1)$$

$$p'=\rho' R T', \qquad u'=-\frac{k'}{\mu'}\frac{\partial p'}{\partial r'} \qquad (2,3)$$

$$\frac{(1-\phi)\ \rho'_r C'_r+\rho' C'_V}{\rho' C'_V}\frac{\partial T'}{\partial t'}+u'\frac{\partial T'}{\partial r'}=$$
$$-\frac{p'}{\rho' C'_V}\frac{1}{r'}\frac{\partial}{\partial r'}(r'u')+$$
$$\frac{1}{\rho' C'_V}\frac{1}{r'}\frac{\partial}{\partial r'}\left(r'K'_m\frac{\partial T'}{\partial r'}\right)+\frac{\mu'}{\rho' C'_V K'}u'^2 \qquad (4)\cdot$$

In order to set the equations in the non-dimensional variables, the following non-dimensional variables are introduced; p'_o, ρ'_o, T'_o are the pressure, density and temperature references at $r' = r'_0$, $t'_R = \sigma k'_o/\alpha'$ is the conduction time reference defined as the characteristic time for heat diffusion to propagate through a distance of an effective pore diameter, and $v'_R = \alpha'/(k_o')^{1/2}$ is the velocity reference defined as a conductive diffusion velocity through a distance of an effective pore diameter.

The governing equations now become

$$\beta\Phi\frac{\partial\rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\,\rho\,u)=0 \qquad (5)$$

$$p=\rho\,T, \ \in u=-\frac{X}{m}\frac{\partial p}{\partial r} \qquad (6,7)$$

$$A\frac{\partial T}{\partial t}+\rho u\frac{\partial T}{\partial r}=-(\gamma-1)\frac{p}{r}\frac{\partial}{\partial r}(ru)+$$
$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,K\frac{\partial T}{\partial r}\right)+\in(\gamma-1)\frac{m}{X}u^2 \qquad (8,9)$$

where $A = 1 + \phi(\rho - F)\beta + (F - 1)\beta$.

The subscripts t and r denote partial derivatives, and

$$(p,\rho,T)=\frac{(p',\rho',T')}{(p'_o,\rho'_o,T'_o)}, r=\frac{r'}{k_o'^{1/2}},$$
$$t=\frac{t'}{\sigma k'_o/\alpha'}, u=\frac{u'}{\alpha'/k_o'^{1/2}} \qquad (10)$$

$$\Phi(r)=\frac{\phi'}{\phi'_o}, \ K(T)=\frac{K'_m}{K'_{m_o}},$$
$$m(T)=\frac{\mu'}{\mu'_o}, \ X(r)=\frac{k'}{k'_o} \qquad \beta=\phi_0/\sigma \qquad (11)$$

Here, $F = \rho_r' C_r' / (\rho_o' C_v')$ is the ratio between volumetric specific heat of matrix rock to that of fluid, $\sigma = (1 - \phi_0) F + \phi_0$, is the ratio between volumetric specific heat of fluid-rock combination to that if only contains fluid, $\alpha' = K'_{mo}/\rho_o' C_v'$, is the fluid diffusivity coefficient, $(k_0')^{1/2}$ is the effective pore diameter, used as a length of reference, and C_0' is the acoustic wave velocity.

A small parameter $\in$ in (8) can be expressed as

$$\in = \frac{\mu_o' \alpha'}{k_o' p_o'} = \frac{\mu_o' C_o' / p_o'}{k_o'^{1/2}} \frac{k_o'^{1/2} / C_o'}{k_o' / \alpha'} \qquad (12)$$

where $(m_o' C_0'/p_o')$ is equivalent to the molecular mean free path, and $t_a' = (k_o'^{1/2}/C_o')$ is the time required for acoustic wave to propagate across a pore diameter. Therefore the parameter $\in$ can be expressed as

$$\in \approx \frac{\text{mean free path}}{\text{effective pore diameter}} \left(\frac{t_a'}{t_R'} \right)_{\text{pore}} \qquad (13)$$

The parameter ,$\in$, is very small, typically, for steam of 200 °C and 1 bar, with rock permeability $k' = 10^{-14}$ m^2, $\in = 2{,}38 \times 10^{-3}$. In the subsequent sections, the governing equations controlling the compression waves propagation for different conditions would be formulated and solved in terms of asymptotic expansions based on the limit $\in \to 0$.

MATHEMATICAL FORMULATION

The purpose of the following investigations is to consider the unsteady wave propagations radially in a system consists of porous medium filled with steam, caused by a pressure disturbance from the midle of the system, with varying conditions of the temperature distribution in the medium.

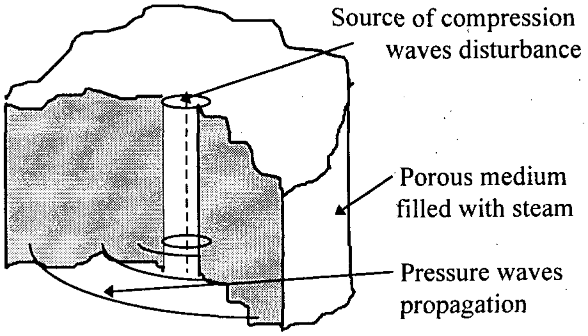

Figure 1. The idealized system

In this work, two basic systems are formulated. The first case is the formulation of a system when a relatively weak pressure disturbance is introduced in medium with a uniform temperature distribution. The second formulation is derived for the case when the weak pressure signals propagate through medium with a non-uniform temperatur distribution having non-uniform permeability and porosity distribution.

The corresponding initial and boundary conditions are of the following form

$t = 0,\ p = 1,\ T = T_b(r),\ u = 0;\ r \geq r_0$
$r = r_0,\ p = 1 + \delta(\in) f(t);\ t \geq 0$

with a specified time-dependent pressure disturbance at the wall of the hole.

Case 1. Uniform Fluid Temperature Formulation

In the case when weak acoustic waves are released from the well, where $(p' - p'_o) / p'_o = O(\in^2)$, the appropriate density, pressure and temperature fluctuations on a time scale $t' = O(\in t_R')$ or $t = \in \hat{t}$ would be

$$(\rho, p, T) = 1 + \in^2 (\hat{\rho}, \hat{p}, \hat{T}) \qquad (14)$$

and the velocity scale would be $u' = O(v_R')$ or $u = \hat{u}$. The leading term on the asymptotic expansions of (14) would be denoted by subscript $(\ )_0$. These variable scales can be found by insisting on a balance between the compression and transient terms in the energy equation (8) giving a set of basic equations which lead to the expression of the pressure waves propagation in the system

$$\frac{\partial \hat{p}_o}{\partial \hat{t}} = \left(\frac{1}{\beta \Phi} + \frac{\gamma - 1}{A_o} \right) \frac{1}{r} \frac{\partial}{\partial r} \left[r X \frac{\partial \hat{p}_o}{\partial r} \right] \qquad (15)$$

which is a form of diffusion equation.

It is to be noted that in an isothermal medium, the viscosity and thermal conductivity of the system would be homogeneous throughout the system, or $m = K = 1$. From the expression (15), one could say that the compression waves propagation in the medium is dominated by its diffusion process, it decays away and smears as time progresses. The decay coefficient depends on the porosity distribution $\Phi(r)$ and the smearing effects would be determined by the system permeability distribution $X(r)$.

Case II. Non-uniform Fluid Temperature Formulation

In this preliminary study, where the porous system is considered to be vapor dominated, it is assumed that initially the system is in equilibrium thermodynamically, having temperature distribution $T_b = T_b(r)$. Consequently its density distribution would be $r_b = 1/T_b$. Again for a very weak pressure signal, the corresponding density, pressure and temperature disturbances could be expressed as

$$(\rho, p, T) = (1/T_b, 1, T_b) + \in^2 (\tilde{\rho}, \tilde{p}, \tilde{T}) \qquad (16)$$

Again as before, the variable scalings in (16) can be found by forcing a balance between the compression and transient terms in equation (8). From the system of equations (7)-(10), one can use (16) to find a set of equations which leads to the characteristic equation which governs the compression waves propagation in the medium as

$$\frac{\partial \tilde{p}_o}{\partial \tilde{t}} = \left[\frac{1}{\beta\Phi} + \frac{\gamma - 1}{A_o T_b}\right] \frac{1}{r} \frac{\partial}{\partial r} \left[r \frac{X}{m} \frac{\partial \tilde{p}_o}{\partial r} \right] + \frac{X}{m} \left(\frac{1}{A_o T_b} - \frac{1}{\beta\Phi} \right) \frac{1}{T_b} \frac{\partial T_b}{\partial r} \frac{\partial \tilde{p}_o}{\partial r} \qquad (17)$$

It is to be noted here that due to the heterogeneity of the radial temperature distribution, the viscosity and thermal conductivity of the system would be functions of local temperature, m(T) and K(T).

The equation shows that, besides the diffusion term on the right hand side, the equation also has an additional term which depends on the gradient of the basic temperature distribution of the medium, $\partial T_b/\partial r$. The nature of the equation, whether it is parabolic or hyperbolic, depends on the magnitude of the coefficients of the two terms on its right hand side. The expression could be a diffusion equation, especially, if the basic system has a uniform temperature distribution, $\partial T_b/\partial r = 0$. However, if the second coefficient in the right hand side becomes more dominant than the first, the equation becomes hyperbolic. The hyperbolicity of the equation (17) is currently under investigation.

The first term of the equation (17) also shows that the compression waves would be more attenuated as it propagates through porous medium with lower basic temperature and porosity. Smearing effects would be amplified when permeability increases and viscosity decreases. On the other hand, the importance of the second term would be determined by the temperature gradient, viscosity, porosity, and permeability distributions.

NUMERICAL FORMULATION AND RESULTS

In order to accommodate the radial geometry of the problem, where in the region closer to the signal source a higher accuracy is preferred, a stretched-coordinate griding technique is employed. The grid spacings are dense in the vicinity of the source, and becomes more sparse for grid points r_i farther from the source,

$$r_i = \Delta N \frac{k^{i-1} - 1}{k - 1} \qquad (18)$$

Here, ΔN and k are the controlling parameters. In order to assure the computational stability, equation (17) is discretized in an implicit formulation as follows,

$$p_i^{n+1} - p_i^n = \frac{2 C_{d_i} \Delta t}{r_i \left(r_{i+1} - r_{i-1} \right)} \left[\frac{\tilde{A}_{i+1/2}}{r_{i+1} - r_i} p_{i+1}^{n+1} + \frac{\tilde{A}_{i-1/2}}{r_i - r_{i-1}} p_{i-1}^{n+1} - \left(\frac{\tilde{A}_{i+1/2}}{r_{i+1} - r_i} + \frac{\tilde{A}_{i-1/2}}{r_i - r_{i-1}} \right) p_i^{n+1} \right] + C_{w_i} \Delta t \frac{X_i}{m_i} \left(\frac{T_b(r_{i+1}) - T_b(r_{i-1})}{r_{i+1} - r_{i-1}} \right) \left(\frac{p_{i+1}^{n+1} - p_{i-1}^{n+1}}{r_{i+1} - r_{i-1}} \right) \qquad (19)$$

where,

$$C_d = \frac{\gamma - 1}{A_o T_b} + \frac{1}{\beta\Phi} \text{ dan } C_w = \left(\frac{1}{A_o T_b} - \frac{1}{\beta\Phi} \right) \frac{1}{T_b} \qquad (20)$$

$$\tilde{A} = \frac{X(r) r}{m(T_b(r))} \qquad (21)$$

A numerical example has been carried out for the case of a radial porous system filled with steam of 200^0C, 1 bar. The uniform, porous rock matrix system has the following characteristics; $\rho_r' = 2500$ kg/m^3, $C_r' = 1500$ J/kg^{0}C, $k_0' = 10^{-11}$ m^2, $\phi = 0.2$, $K'_{m0} = 1.1$ W/m^{0}K. The reference time $t_R' = 2.369 \times 10^{-5}$ sec., $\in = 2.0799 \times 10^{-2}$, $\in^2 = 0.31 \times 10^{-3}$ with an effective pore diameter, $(k'_0)^{1/2} = 0.31 \times 10^{-5}$ m. The calculated parameters, $F = 3.806 \times 10^3$, $\sigma = 3.045 \times 10^3$, $\beta = 0.6569 \times 10^{-3}$, and $\alpha = 1.2854 \times 10^{-3}$ m^2/sec.

Table 1. The first maximum pressure and behavior of the propagating waves at each location, due to 5 Hz and 0.5 Hz pressure disturbances

	5 Hz Pressure Signal		0.5 Hz Pressure Signal	
Location	Pressure (bars)	Behavior	Pressure	Behavior
0.316 m	0.1402	--	0.1402	--
0.471 m	0.04440	sinusoidal	0.0873	sinusoidal
0.701 m	0.01019	wavy	0.04743	sinusoidal
1.044 m	0.1606 X 10-2	wavy	0.02142	wavy
1.554 m	0.3796 X 10-3	damped	0.7482 X 10-2	wavy
2.314 m	0.6181 X 10-5	---	0.1243 X 10-3	wavy

For the case with a non-uniform temperature distribution, the basic temperature for the porous medium is defined as

$$\begin{aligned} T_b(r) &= T_{max} - (T_{max}-T_{min}).(r-r_0)/(A-r_0) \quad ; \quad r < A \\ &= T_{min} + (T_{max}-T_{min}).(r-A)/(B-A) \quad ; \quad A < r < B \\ &= T_{max} \quad ; \quad r > B \end{aligned} \tag{22}$$

where the maximum temperature, $T'_{max} = 200\,^0C$, and the pressure variation imposed as the signal source is specified as

$$p = A_{mpl} \,.\, \sin(2.\pi.f.t) \tag{23}$$

with an amplitude of the pressure signal, $A_{mpl} = 0.1402$ bar, and constant frequencies. For the following results, $\Delta N = 0.001$, and $k = 1.01$ are used.

The results are presented in Fig. 2 to 5 for a 5 Hz pressure signal. In this case, uniform permeability and porosity assumptions, $\Phi = X = 1$, are used. The results show pressure variations at 5 different locations, $r_0 = 0.471$ m, 0.701 m, 1.044 m, 1.554 m, and 2.314 m. For a similar sinusoidal pressure disturbance with frequency 0.5 Hz, the resulting pressure variations at those locations are illustrated in Fig. 6 to 8. The comparison between the two results is tabulated on Table 1.

It can be shown from Fig. 2 to 8 that pressure signals with higher frequencies are damped more rapidly than that with lower frequencies. At 0.471 m, the 0.5 Hz signal has a first maximum pressure almost twice of that with the 5 Hz signal. The first maximum pressure applying the 0.5 Hz signal, at 0.701 m is more than 5 times, at 1.044 m is almost 13 times, and at 2.314 m is about 20 times stronger than that with the 5 Hz signal. Furthermore, at 0.701 m, the 0.5 Hz signal is still sinusoidal, and the wavy character is still dominant at 2.314 m. While using the 5 Hz signal, the sinusoidal character is already distorted at 0.701 m, the wavy profile is badly damped at 1.554 m, and disappears at 2.314 m. All results indicate that as the waves spread into wider and wider coverages, the pressure disturbances become more and more weakened.

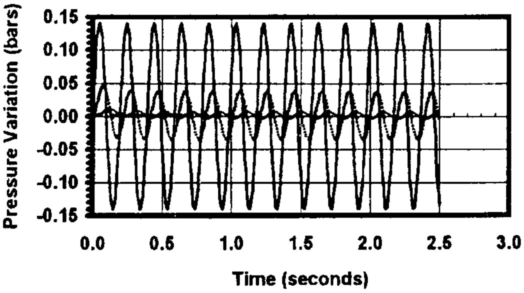

Fig. 2 Pressure variations at various locations due to a 5 Hz pressure signal. At the system inner boundary ($r'_0 = 0.316$ m), and $r' = 0.471$ m, 0.701 m.

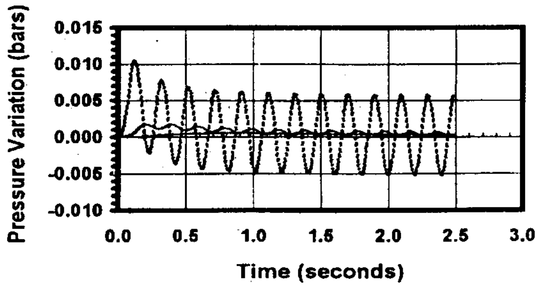

Fig. 3 Pressure variations at various locations due to a 5 Hz pressure signal. At $r' = 0.701$ m, 1.044 m, 1.554 m.

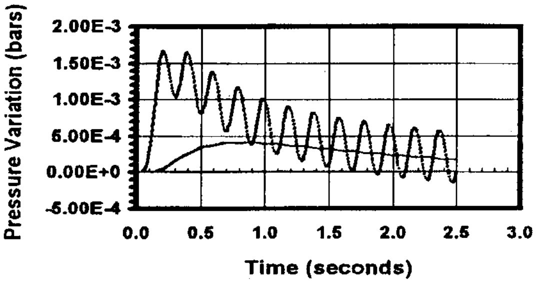

Fig. 4 Pressure variations at various locations due to a 5 Hz pressure signal. At r' = 1.044 m, 1.554 m.

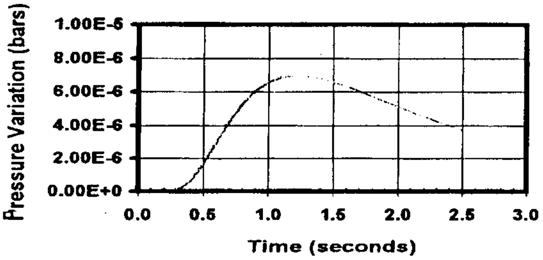

Fig. 5 Pressure variations at r' = 2.314 m due to a 5 Hz pressure signal.

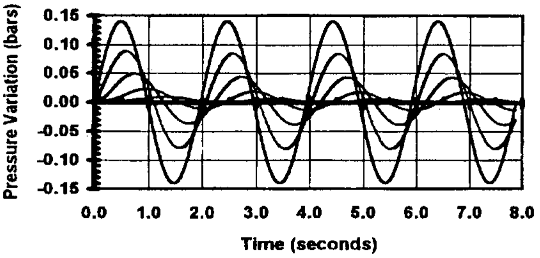

Fig. 6 Pressure variations at various locations due to a 0.5 Hz pressure signal. At the system inner boundary (r'_0 = 0.316 m), and r' = 0.471 m, 0.701 m, 1.044 m.

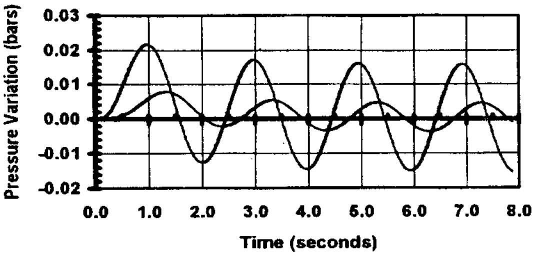

Fig. 7 Pressure variations at various locations due to a 0.5 Hz pressure signal. At r' = 1.044 m, 1.554 m.

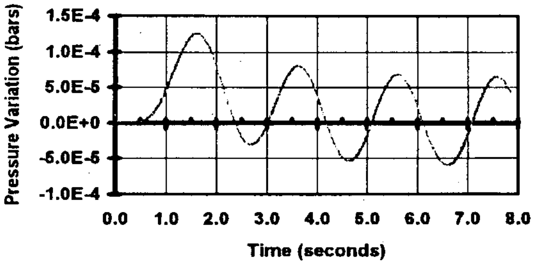

Fig. 8 Pressure variations at r' = 2.314 m due to a 0.5 Hz pressure signal.

The propagation of compression waves through a non-uniform base temperature system (22) has been solved numerically. Temperature distribution in this typical example is defined by choosing $T'_{min} = 0.2\ T'_{max}$, $r'_0 = 0.316$ m, A' = 0.332 m, and B' = 0.348 m, and applying fluid viscosity model, $m(T) = T^{0.7}$. The resulting pressure transients at several different locations, $r_0 = 0.701$ m, 1.044 m, and 1.554 m are presented in Fig. 9. The result of comparison between its pressure transient at $r_0 = 0.701$ m with that for the case of uniform temperature distribution is tabulated in Table 2.

The most obvious differences between those pressure variations are the magnitude of the peak pressures. From Table 2, one can find that the system with non-uniform temperature distribution has higher pressure amplitudes than that with uniform temperature distribution. It is unfortunate that the numerical technique adopted in this investigation cannot resolve the phase shift of the signal due to non-uniformity of the temperature distribution.

The aditional case, for systems with non-uniform temperature distributions, having non-uniform permeability and porosity distributions, the results are presented on Fig. 10 and 11. The permeability distribution is defined by

$X = X_0 + (X_A - X_0).(r - r_0)/(r_A - r_0)$ for $r_0 < r < r_A$,
$X = X_0$ for $r \leq r_0$, and
$X = X_A$ for $r \geq r_A$.

and the porosity distribution is described as

$\phi = \phi_0 + (\phi_A - \phi_0).(r - r_0)/(r_A - r_0)$ for $r_0 < r < r_A$,
$\phi = \phi_0$ for $r \leq r_0$, and
$\phi = \phi_A$ for $r \geq r_A$.

Table 2. Comparison on 5 maximum and minimum peak pressures due to a 5 Hz pressure disturbance between a system with a uniform basic temperature (Fig.3) and that with a nonuniform basic temperature (Fig. 9).

	Uniform Basic Temperature		Non-uniform Basic Temperature	
Pressure Peak	Maximum	Minimum	Maximum	Minimum
1st	0.01019	-0.00232	0.01181	-0.00324
2nd	0.00756	-0.00378	0.00882	-0.00484
3rd	0.00666	-0.00438	0.00785	-0.00547
4th	0.00625	-0.00468	0.00741	-0.00579

The results are presented in Figure 10 and 11. In Fig. 10, $X_A=1.25X_0$, in Fig. 11, $X_A=0.75\ X_0$, and in both cases a similar porosity distribution $\phi_A = 4.25\ \phi_0$ is used. In order to exploit the more detailed behavior of the compression waves propagation in a non-uniform porous medium system, further investigation should be pursued, especially on the detailed characteristic of the exact solution to equation (17).

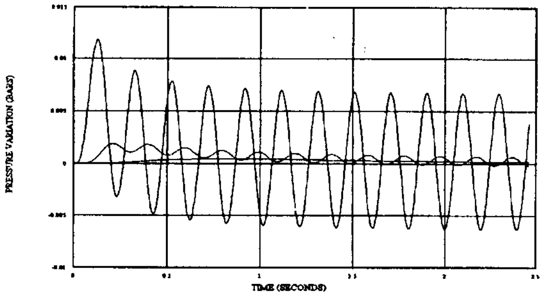

Fig. 9 Pressure variations at various locations in a non isothermal system due to a 5 Hz pressure signal. r' = 0.701 m, 1.044 m, 1.554 m. The case of $X_A = X_0$.

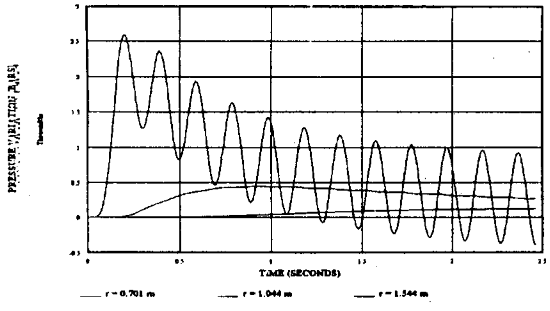

Fig.10 Pressure variations at various locations in a non isothermal system due to a 5 Hz pressure signal. r' = 0.701 m, 1.044 m, 1.554 m. The case of $X_A = 1.25\ X_0$.

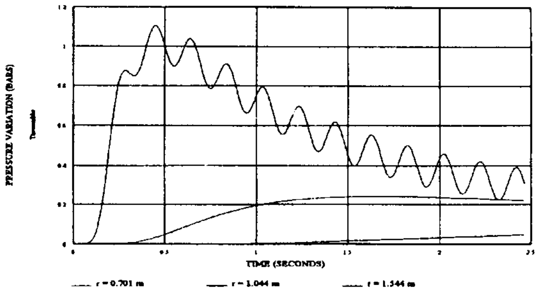

Fig. 11 Pressure variations at various locations in a. non isothermal system due to a 5 Hz pressure signal. r' = 0.701 m, 1.044 m, 1.554 m. The case of $X_A = 0.75\ X_0$.

CONCLUSIONS

Preliminary theoretical investigations have been carried out to study the nature of compression waves propagation through a radial system of porous medium filled with steam. In this relatively weak disturbed system, the steam is assumed to behave as an ideal gas, and the resulting flow motion obeys the Darcy's law.

The analysis is partly focused on a system with a uniform temperature distribution. When the system is disturbed by relatively high frequency, sinusoidal compression waves, it is found that the signal decays away rapidly as it moves through the porous medium. When the frequency of the signal is reduced, the wave attenuation is weaker, and the waves can propagate over longer distance away. It is found that the strength of the signal is significantly weakened as time progresses. It is suspected that the signal weakening is due to its spreading effect since the area covered becomes wider as the signal propagate farther away from the source.

A preliminary study on a system with non-uniform basic temperature has been initiated. The existing temperature gradient in the system gives an additional effect on the originally diffusive system. An evidence of signal amplification due to temperature gradient in the system needs further studies.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Dr. Ir. Soekrisno and Dr. Ir. Indarto for the enthusiasms in bringing this theoretical study to the preparations of an experimental work, and deep appreciation to Ir. Budianto Toha, MSc for the fruitful discussions and helpful suggestions to this work. This work has been supported by research grant from PERTAMINA, to whom the authors are truly thankful.

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