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Modeling and Analysis of Viscous Dissipation Effect on Temperature in the Liquid Explosive Injection Process

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A B S T R A C T

Typically, viscous liquid explosives are injected into the warhead . The injection device consists of a piston which moves downward and leads the viscous fluid through a cylindrical duct towards the end of the duct. Then the viscous fluid entered into a converging nozzle and injected into the warhead or other ammunitions. This article is an analysis of heat transfer of fluid flow of the liquid explosive in the converging nozzle, as a part of the injection device under exposer of heat flux from the walls. Also, viscous dissipation phenomenon is considered, which is due to the viscosity of the fluid. It will raise the fluid temperature. Forced convection heat transfer is investigated analytically. Fully developed laminar flow is assumed. This analysis is done by considering wall heating and wall cooling. By comparing the effect of viscous dissipation and heat flux, it is investigated that effect of which of them is more significant. Axial heat conduction is neglected. Physical properties are assumed to be constant. The theoretical analysis of the steady heat transfer in nozzle flow for non-Newtonian fluid with considering viscous dissipation term in energy equation is performed by an analytical method. An important feature of this approach is obtaining steady temperature distribution of explosive fluid in converging pipe flow with viscous dissipation. Effects of the inlet velocity and density of liquid explosive on the distribution of temperature are presented. Also, the effect of changing the convergence angle on heat transfer is investigated.

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NOMENCLATURE

V	Fluid velocity (m/s)
u_r	Radial pipe velocity (m/s)
$\dot{u}_x$	Axial pipe velocity (m/s)
X	Axial Dimension (m)
t	Time (s)
g	Gravity(m/s^2)
r	Inner radial (m)
ρ_f	fluid density (kg/m^3)
l	Length of converging pipe (m)
μ	Apparent viscosity

1. INTRODUCTION

Viscous liquid explosives are injected into the warhead by discharge system, as shown in Figure 1. Viscous dissipation will affect the heat transfer rate by playing a role like an energy source and changing the temperature distributions. Cooling or heating of the converging pipe will affect the viscous dissipation. Many studies involving pipe and converging pipe flows in the past have neglected the effect of viscous dissipation or considering a small term of general form of viscous dissipation equation. In fact, the shear stresses can induce a considerable thermal energy. However, in the

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past literatures about convective heat transfer, this effect usually regarded as important only in flow of very viscous fluids. The effects of viscous dissipation in laminar flows have not yet been deeply investigated. For liquids with high viscosity and low thermal conductivity, disregarding the viscous dissipation can cause appreciable errors.

Most of the past works considered different conditions for energy equation and solved energy equations using different mathematic methods. Viscous dissipation term is neglected in some of these solutions [1-3]. However, in some of the researches viscous dissipation was involved in energy equation [4, 5]. The energy equation is solved by considering axial heat conduction term in some of the studies [6-8]. Some researchers presented a solution of problem considering the changes in fluid properties due to temperature variation [9, 10].

Barletta studied the viscous dissipation effect on the behaviour of fully developed power law fluid flow including laminar forced convection under a wall heat flux prescribed to a circular tube [11]. Valko used Laplace transform Galerkin technique for modified power law fluid in a circular tube with general boundary conditions. He focused on analysis of the viscous dissipation effects on forced convection [12]. Duvautand Lions studied analytically the velocity and temperature of the Bingham plastic fluid with variable viscosity and temperature [13]. Soares and his colleagues used the finite volume method to study Herschel-Bulkley developed fluid flow in a pipe for both rheological properties such as temperature-dependency and inviscid flow [14]. Nouar studied combination of forced and free convection heat transfer in a rectangular duct Herschel-Bulkley fluid which is heated uniformly under a constant heat flux [15].

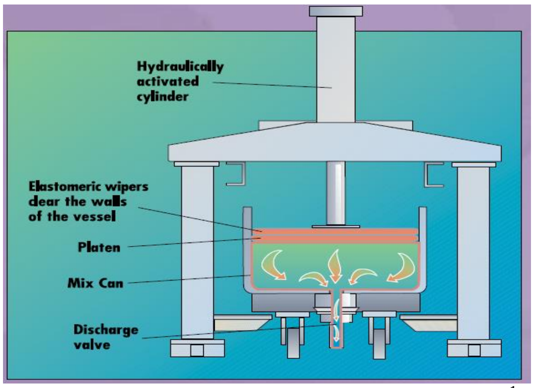

Figure 1. Schematic of ross&son discharge system[1]

[1] C Charles Ross & Son Company, Dischare systems, producer of discharge instruments, http://www.mixers.com, 2016

Cortell investigated the effect of viscous dissipation on heat transfer properties for an incompressible fluid on a stretched second order sheet [16].

Siddiqui and colleagues by using of homotopy perturbation method studied a thin film of fluids flow of Oldroyd 6 and Sisko onto a moving belt [17]. Siddheshwar and his colleague studied the effects of radiation and thermal source on a magnetic hydrodynamic fluid of the viscoelastic solution; also they studied heat transfer on a stretch sheet [18]. Vinay and his colleagues studied non-isothermal visco-plastic raw wax fluid by numerical simulation [19]. Peixinho and his colleagues studied an experimental on forced convective heat transfer for Carbopol water by considering a transient regime, regardless of viscous dissipation [20]. Aydin and Orhan studied viscous dissipation effects on the forced heat transfer of a hydrodynamic and a fully developed fluid in the pipe [21]. Kishan and his colleagues by assuming radiant heat transfer, viscous dissipation and power law model studied a hydrodynamic magnetic fluid on a nonlinear drawn surface [22]. In addition to the treatment of power law fluid, the effects of viscous dissipation for a third order fluid was tested by Massoudi and Christie [23].

An investigation has been made to analyze the effects of viscous dissipation on the heat transfer characteristics for both hydro-dynamically and thermally fully developed, laminar shear driven flow between two infinitely long parallel plates by Pranab Mondal and Mukherjee [24]. The problem of forced convection over a horizontal flat plate under condition of variable plate temperature is presented with homotopy perturbation method (HPM) by Ganji and his colleague [25].

In this paper, an analytical solution of the steady heat transfer is obtained for explosive fluid flow in converging pipe, considering general form of viscous dissipation term in energy equation. Furthermore, effect of the pipe convergence angle, inlet velocity of fluid, density change of the explosive and other properties of fluid on temperature distribution is investigated.

2. ANALYSIS

The flow is assumed to be unsteady, laminar and fully thermally developed with constant properties (i.e. the thermal diffusivity and the thermal conductivity of the fluid are considered to be independent of temperature). The axial heat conduction in the fluid and in the wall is assumed to be negligible.

General form of the viscous dissipation term [26] in the cylindrical coordinate is as below

$$\Phi = 2\left[\left(\frac{\partial u_r}{\partial r}\right)^2 + \left(\frac{1}{r}\frac{\partial u_\phi}{\partial \phi} + \frac{u_r}{r}\right)^2 + \left(\frac{\partial u_x}{\partial x}\right)^2\right] + \left[r\frac{\partial}{\partial r}\left(\frac{u_\phi}{r}\right) + \frac{1}{r}\frac{\partial u_r}{\partial \phi}\right]^2 + \left[\frac{1}{r}\frac{\partial u_z}{\partial \phi} + \frac{\partial u_\phi}{\partial x}\right]^2 + \left[\frac{\partial u_r}{\partial x} + \frac{\partial u_x}{\partial r}\right]^2 - \frac{2}{3}\left[\frac{1}{r}\frac{\partial}{\partial r}(r u_r) + \frac{1}{r}\frac{\partial u_\phi}{\partial \phi} + \frac{\partial u_x}{\partial x}\right]^2 \quad (1)$$

The viscous dissipation term for one dimensional and incompressible fluid,

$$\phi = 2\left[\left(\frac{\partial u_r}{\partial r}\right)^2 + \left(\frac{u_r}{r}\right)^2\right] - \frac{2}{3}\left[\frac{1}{r}\frac{\partial}{\partial r}(r u_r)\right]^2 \quad (2)$$

The energy equation [27] in direction of r is given by:

$$\rho c u\left(\frac{\partial T}{\partial t} + \frac{\partial T}{\partial x}\right) = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}\right] + \mu_{apr}\Phi \quad (3)$$

The second term on the right-hand side is viscous dissipation.

Substituting the Φ term,

$$\rho c u\left(\frac{\partial T}{\partial t} + \frac{\partial T}{\partial x}\right) = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right] + \mu_{apr}\left(2\left[\left(\frac{\partial u_r}{\partial r}\right)^2 + \left(\frac{u_r}{r}\right)^2\right] - \frac{2}{3}\left[\frac{1}{r}\frac{\partial}{\partial r}(r u_r)\right]^2\right) \quad (4)$$

For the case of uniform wall heat flux, the first term on the left-hand side of Equation (4) is:

$$\frac{\partial T}{\partial x} = \frac{dT_w}{dx} = const \quad (5)$$

Using the continuity equation

$$\rho u A = \rho_0 u_0 A_0 \quad (6)$$

By assuming incompressible fluid flow

$$u(\ell) = \frac{u_0 r_0^2}{r_0^2 + \ell^2 \tan^2\alpha - 2 r_0 \ell \tan\alpha} \quad (7)$$

where

$$\frac{k}{\rho c_p} = \alpha = \frac{\nu}{pr} \quad (8)$$

$$\rho c(r_0 - \ell\tan\theta)\tan\theta = a \quad (9)$$

$$r_0^2 + \ell^2\tan^2\theta - 2r_0\ell\tan\theta = b \quad (10)$$

$$-2\ell\tan^2\theta + 2r_0\tan\theta = m \quad (11)$$

$$r_0 - \ell\tan\theta = n \quad (12)$$

By replacing the above terms in the velocity equation, the energy equation will be obtained as follows:

$$\frac{(kr_0)T''(\ell)}{a\tan(\theta)} - \frac{(k\ell)T''(\ell)}{a} - \frac{kT'(\ell)}{a} + \frac{\left(\frac{\mu_{apr}}{\rho c_p}\right)(m^2 r_0^4 u_0^2)}{b^4\tan^2(\theta)} - \left(\frac{(2\mu_{apr})}{(3c_p p)}\right)\times\left[\left(\frac{\frac{(-n)(mr^2u_0)}{b^2\tan(\theta)} + \frac{r_0^2 u_0}{b}}{n}\right)^2\right] + \left(\frac{\mu_{apr}}{\rho c_p}\right)\left(\frac{r^2u_0}{bn}\right)^2 - \frac{r^2u_0\, dT_w/d\ell}{b} = 0 \quad (13)$$

The form of unsteady energy equation can be written as:

$$\frac{\partial T}{\partial t} + \frac{(kr_0)T''(\ell)}{a\tan(\theta)} - \frac{(k\ell)T''(\ell)}{a} - \frac{kT'(\ell)}{a} + \frac{\left(\frac{\mu_{apr}}{\rho c_p}\right)(m^2 r_0^4 u_0^2)}{b^4\tan^2(\theta)} - \left(\frac{(2\mu_{apr})}{(3c_p p)}\right)\times\left[\left(\frac{\frac{(-n)(mr^2u_0)}{b^2\tan(\theta)} + \frac{r_0^2 u_0}{b}}{n}\right)^2\right] + \left(\frac{\mu_{apr}}{\rho c_p}\right)\left(\frac{r^2u_0}{bn}\right)^2 - \frac{r^2u_0\, dT_w/d\ell}{b} = 0 \quad (14)$$

To solve the steady energy equation given in Equation (13), the boundary conditions are given as follows:

$$T = T_0 \quad at \ \ell=0 \quad (15)$$

$$\frac{dT}{d\ell} = 0,\ at\ r=0 \quad (16)$$

Parameter ℓ is the height of converging pipe.

Steady heat transfer in converging pipe flow is as below

$$
\begin{aligned}
T = {} & \frac{1}{48k}\left[\begin{aligned} & 24c_p \rho r_0^2 u_0 \frac{dT_w}{d\ell} \log^2(-r_0 \cos(\theta)) + \\ & 60 c_p \rho \left(\frac{\mu_{apr}}{\rho c_p}\right) u_o^2 \log(-r_0 \cos(\theta)) \\ & +15 c_p \rho \left(\frac{\mu_{apr}}{\rho c_p}\right) u_0^2 - 8\mu_{apr} u_0^2 \times \\ & \log(-r_0 \cos(\theta)) - 2\mu_{apr} u_0^2 + 48kT_0 \end{aligned}\right] + \\
& \frac{1}{96} \times \\
& \left[\frac{1}{k} \times \left[\left[\begin{aligned} & 2r_0^2 u_0 \times \\ & \left(\frac{r_0^2 u_0 \cos^4(\theta) \left(2\mu_{apr} - 15 c_p \rho \left(\frac{\mu_{apr}}{\rho c_p}\right) \right)}{(r_0 \cos(\theta) - \ell \sin(\theta))^4} \right. \end{aligned} \right] + \left[24 c_p \rho \frac{dT_w}{d\ell} \log^2 \left(\begin{aligned} & \ell \sin(\theta) - \\ & r_0 \cos(\theta) \end{aligned} \right) \right) \right] \right. \\
& + \frac{1}{12k} \left[\begin{aligned} & 96 \csc(\theta) \log(\ell \sin(\theta) - r_0 \cos(\theta))(u_0 \sin(\theta) \\ & (-12 c_p \rho r_0^2 \frac{dT_w}{d\ell} \log(-r_0 \cos(\theta)) \\ & -15 c_p \rho \left(\frac{\mu_{apr}}{\rho c_p}\right) u_0 + 2\mu_{apr} u_0) \end{aligned} \right] \Bigg]
\end{aligned} \tag{17}
$$

3. RESULTS&DISSCUSION

In this paper, Forced convection heat transfer in a non-Newtonian fluid flow inside converging pipe is investigated analytically.

3. 1. Temperature Distribution inside the Converging Pipe for Positive Heat Flux

The temperature distribution in the converging pipe is shown in Table 1 and Figure 3 to show positive state of flux. As can be seen, towards the end of the nozzle L=0.4, the fluid velocity will increase proportional to the decreasing of cross-section area. So, this increase will be effective on ramping of fluid temperature inside the nozzle. For a state that the wall is warming under constant positive flux, this rate of increasing temperature will be more rapid due to the increasing convergence angle. By comparing the temperature at a constant L, it can be seen that by increasing the convergence angle from 15 ° to 60 °, the temperature at the fixed position L of converging pipe is increased to approximately six or seven degreed of Celsius, just by changing the convergence angle. The following values was used for the current flow in the nozzle:

$\frac{dT_w}{dx} = +0.1$ *and -0.1*

$\mu = 0.001$

$\rho = 1896 \ {}^{kg}/_{m^3}$

$C_p = 2.907$

$T_0 = 288.15\ \dot{k}$

$k=0.5$

TABLE 1. Temperature distribution for steady fluid flow through converging pipe for positive heat flux

	$\theta = \frac{\pi}{12}$	$\theta = \frac{\pi}{6}$	$\theta = \frac{\pi}{4}$	$\theta = \frac{\pi}{3}$
L	T	T	T	T
0	288.15	288.15	288.15	288.15
0.05	288.151	288.1548	288.16469	288.1963
0.10	288.1541	288.1698	288.2129	288.359
0.15	288.1593	288.1963	288.3020	288.6939
0.20	288.1669	288.2357	288.4419	289.2857
0.25	288.176	288.2896	288.6452	290.2922
0.30	288.1895	288.3599	288.9292	292.0275
0.35	288.2048	288.4490	289.3177	295.2415
0.40	288.2229	288.5593	289.8448	302.4026

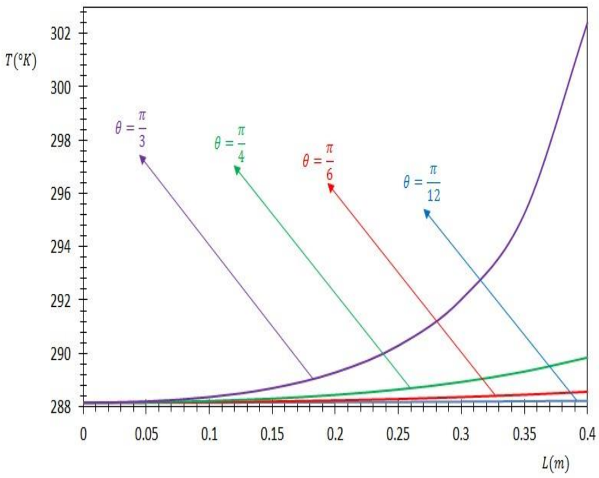

Figure 3. Effect of convergence angle on temperature distribution for steady fluid flow through converging pipe for positive heat flux

3. 2. Temperature Distribution inside the Converging Pipe for Negative Heat Flux In Table 2 and Figure 4 the temperature distribution in the converging pipe for negative state of flux is shown. As can be seen, towards the end of the nozzle L=0.4, the fluid velocity will increase proportional to decreasing of cross-section area. So, this increase will be effective on ramping of fluid temperature inside the nozzle. For a state that the wall is cooling under constant negative flux, this rate of decreasing temperature will be more rapid due to the increasing convergence angle. By comparing the temperature at a constant L, it can be seen that by increasing the convergence angle from 15 ° to 60 °, the temperature at fixed location L of converging pipe is decreased to approximately 15 degrees Celsius, just by changing the convergence angle.

In fact, by increasing the velocity, the convective heat transfer will increase. Therefore, it will be effective on cooling or warming of fluid. The fluid temperature due to internal heat dissipation due to the viscosity of Non-Newtonian fluid temperature tends to increase. Because it is under wall negative heat flux, decreasing of wall temperature is more important and effectiveness is proportional to the viscous dissipation. Negative heat flux is more important, so in the end, the fluid temperature will have a decrease inside the nozzle.

3. 3. Effect of Input Velocity of Fluid on Temperature Distribution

3. 3. 1. For Positive Heat Flux Increase in the velocity will increase the strain rate and shear stress on the fluid. So, naturally increase the viscous dissipation and therefore generated heat in the fluid. As can be seen, increase in input fluid velocity will causes increase of the heat generation due to viscous dissipation and positive heat flux from the heat input from the walls. In fact, the temperature increased up to about 70°C by increase of the velocity (see Table 3 and Figure 5).

3. 3. 2. For Negative Heat Flux Increase in the velocity will increase the strain rate and shear stress on the fluid. Therefore, naturally increasing in the viscous dissipation may generated heat in the fluid. As can be seen, increase in the fluid velocity will causes decrease of the heat generation due to viscous dissipation and negative heat flux from the walls. Because the negative heat flux to the walls is more significant than the heat generation due to viscous dissipation, therefore, the temperature decreased up to about 57°C by increase of velocity of flow intended for a fluid (see Table 4 and Figure 6).

TABLE 2. Temperature distribution for steady fluid flow through converging pipe for negative heat flux

	$\theta=\frac{\pi}{12}$	$\theta=\frac{\pi}{6}$	$\theta=\frac{\pi}{4}$	$\theta=\frac{\pi}{3}$
L	T	T	T	T
0	288.15	288.15	288.15	288.15
0.05	288.1489	288.1452	288.1353	288.1037
0.1	288.14591	288.1302	288.0871	287.9400
0.15	288.1406	288.1037	287.9979	287.6060
0.2	288.1330	288.0643	287.8581	287.0143
0.25	288.1230	288.0103	287.6548	286.0078
0.3	288.1104	287.9400	287.3708	284.2724
0.35	288.0952	287.8510	286.9822	281.0584
0.40	288.0770	287.7407	286.4552	273.8970

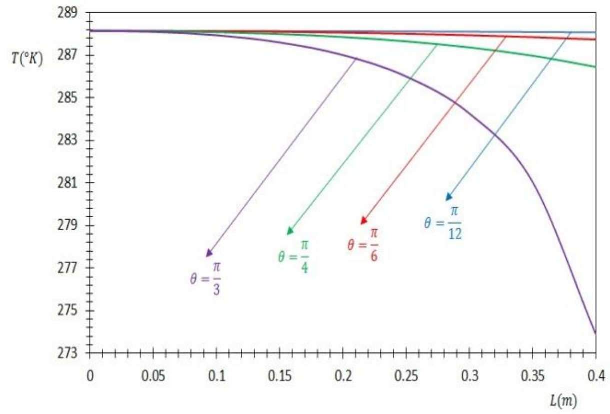

Figure 4. Effect of convergence angle on temperature distribution for steady fluid flow through converging pipe for negative heat flux

TABLE 3. Effect of input velocity of fluid on temperature distribution for steady fluid flow through converging pipe for positive heat flux

	$u_0=0.01$	$u_0=0.02$	$u_0=0.03$	$u_0=0.04$	$u_0=0.05$
L	T	T	T	T	T
0	288.15	288.15	288.15	288.15	288.15
0.05	288.1489	288.2420	288.2889	288.3352	288.3815
0.10	288.14591	288.5699	288.7799	288.9899	289.1999
0.15	288.1406	289.2379	289.7818	290.3257	290.8697
0.20	288.1330	290.4214	291.5571	292.6928	293.8285
0.25	288.1230	292.4343	294.5765	296.7187	298.8608
0.30	288.1104	295.9051	299.7826	303.6602	307.5376
0.35	288.0952	302.3330	309.4244	316.5158	323.6072
0.40	288.0770	316.6549	330.9069	345.1586	359.4090

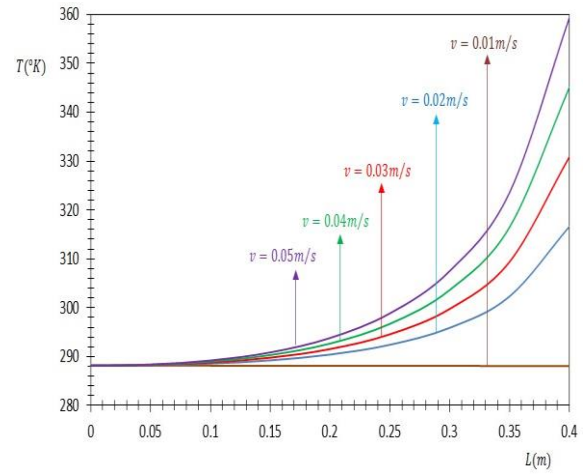

Figure 5. Effect of input velocity of fluid on temperature distribution for steady fluid flow through converging pipe for positive heat flux

TABLE 4. Effect of input velocity of fluid on temperature distribution for steady fluid flow through converging pipe for negative heat flux

	$u_0 = 0.01$	$u_0 = 0.02$	$u_0 = 0.03$	$u_0 = 0.04$	$u_0 = 0.05$
L	T	T	T	T	T
0	288.15	288.15	288.15	288.15	288.15
0.05	288.1037	288.0573	288.0111	287.9648	287.9185
0.10	287.9400	287.7300	287.5200	287.3100	287.1000
0.15	287.6060	287.0621	286.5182	285.9742	285.4303
0.20	287.0143	285.8785	284.7428	283.6071	282.4714
0.25	286.0078	283.865	281.7234	279.5813	277.4391
0.30	284.2724	280.3948	276.5173	272.6397	268.7621
0.35	281.0584	273.9668	266.8752	259.7836	252.6919
0.40	273.8970	259.6437	245.3900	231.1360	216.8816

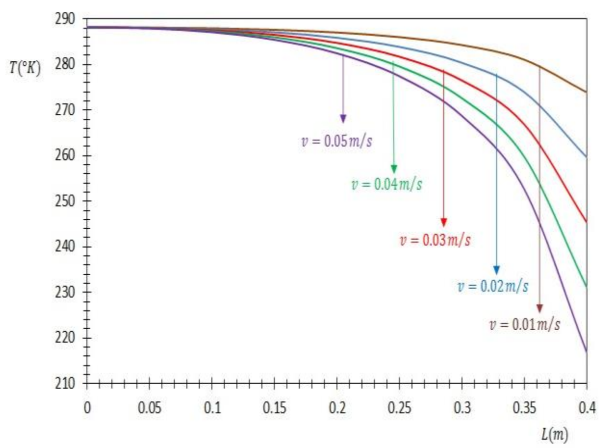

Figure 6. Effect of input velocity of fluid on temperature distribution for steady fluid flow through converging pipe for negative heat flux

3. 4. Effect of The Explosive Material (PBX) with Different Density on Temperature Distribution for Steady Fluid Flow through Converging Pipe with Positive Heat Flux

In Table 5, effects of the explosive materials (PBX) with different density are presented. As can be seen, increasing the density will causes increase in the viscosity of fluid, shear stress and heat production, and consequently increase the temperature of the non-Newtonian fluid. As mentioned, the temperature is increased by increasing the density.

TABLE 5. The effects of explosive material (PBX) with different density on temperature distribution for steady fluid flow through converging pipe with positive heat flux

	PBX-9502	PBX-9404	PBX-9404	PBX-9404	PBX-9404
Density (kg/m^3)	1896	1846	1845	1844	1840
L	T	T	T	T	T
0.1	288.7799	288.7633	288.7630	288.7627	288.7613
0.2	291.5571	291.4672	291.4655	291.4637	291.4565
0.3	299.7826	299.4758	299.4697	299.4635	299.4390
0.40	330.9070	329.7793	329.7568	329.7342	329.6440

4. CONCLISION

Both convergence angle and fluid velocity are effective on temperature as explained below:

1. When the wall of nozzle is warming up under fixed positive heat flux, the rate of temperature increase will be more rapid than temperature increase due to the increment of convergence angle. By increasing the convergence angle from 15° to 60°, the temperature at a fixed position of the pipe height is increased up to approximately six or seven degrees Celsius, just by changing the convergence angle.

For negative heat flux, decreasing of wall temperature is more important and effective comparing to the viscous dissipation. So, by increasing the convergence angle from 15° to 60°, the temperature at the constant height value of converging pipe is decreased to approximately 15 degrees Celsius, just by changing the convergence angle.

2. Increasing fluid regime velocity will causes increasing of the heat due to viscous dissipation and positive heat flux from the heat input from the walls. In fact, the temperature increased up to about 70°C by increase of velocity of flow.

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Modeling and Analysis of Viscous Dissipation Effect on Temperature in the Liquid Explosive Injection Process

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چکیده

به طور معمول سیال لزج انفجاری توسط دستگاه تخلیه شارژ به سرجنگی تزریق می‌شود. این دستگاه تزریق متشکل از یک پیستون با سطح مقطع دایروی است که با حرکت به سمت پایین سیال لزج را در یک مجرای لوله‌ای استوانه‌ای شکل به سمت انتهای مجرا هدایت می‌کند. سپس این سیال لزج وارد مسیری هم‌گرا شکل گردیده و توسط این نازل به سر جنگی یا سایر مهمات تزریق می‌گردد. در این مقاله، انتقال حرارت و جابجایی سیال انفجاری در بخشی از مسیر تزریق که به شکل لوله‌ی هم‌گرا می‌باشد و تحت شار حرارتی دریافتی از دیواره‌هاست، به صورت تحلیلی ارایه شده است. در مقاله‌ی حاضر پدیده‌ی اتلاف لزجتی که سبب افزایش دما می‌شود در معادله‌ی انرژی وارد شده است. با در نظر گرفتن خواص فیزیکی ثابت، جریان کاملاً توسعه یافته و جریان آرام برای هر دو حالت گرم شدن یا سرد شدن دیواره، آنالیز حرارتی انجام پذیرفته است. با مقایسه‌ی توزیع دما، اهمیت پدیده اتلاف لزجتی و شار حرارتی مقایسه شده است. همچنین، تاثیرات سرعت ورودی، چگالی مواد منفجره و زاویه‌ی هم‌گرایی مجرا بر روی انتقال حرارت بررسی شده است..

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