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Simulation of Fluid Flow In The Exhaust of An Internal Combustion Engine

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Abstract

Internal combustion engine design is a complex and costly process due to the large number of variables that affect the design. Simulation of fluid flow plays a very important role in the development of engine. Fluid flow in an Internal Combustion Engine exhaust system has been simulated. A non-Linear, Hyperbolic, Partial Differential Equation was solved using Galerken`s Finite element method. The resulting matrix equations were solved for the Exhaust Manifold, the Catalytic Converter, the Muffler and the Tail Pipe. Using excel program. The results (data) obtained were plotted.

Introduction

Automobile is one of the fastest growing industries in the world today, because of the importance of transportation and mechanize agriculture virtually every nation is working hard to improve or to develop her indigenous automobile industry. Despite that the technology seems to be widely spread across the continents there is still room for research, which is left for competition that is, efficiency in all aspect of the automobile from engine performance to emission control system. So far the following methods has been used, Quasi-steady, Filling and emptying and wave action.

The purpose of internal combustion engines is the production of mechanical power from the chemical energy contained in the fuel. In internal combustion engines, as distinct from external combustion engines, this energy is released by burning or oxidizing the fuel inside the engine. The fuel-air mixture before combustion and the burning products after combustion are the actual working fluids. The work transfers which provide the desired power output occur directly between these working fluids and the mechanical components of the engine.

Methodology

Attempt was made to simulate Fluid Flow in the exhaust system of an internal combustion engine. By using:

1. The governing equations of fluid flow, momentum, continuity equation and energy equation and use it to evaluate the unsteady flow of gas in engine manifold.
2. Finding numerical solution to the Non-Linear, partial differential equations developed which will be used in predicting the extremely complex situation in internal combustion engine exhaust.
3. Predicting the pressure at the exhaust components of an internal combustion engine at any given time.
4. Predict the pressure and density of flow in the components of the exhaust system at any point, at any given time.

Governing Equation

The governing equation was derived from continuity, momentum and energy combining them yield the governing equation of flow for the one-dimensional flow of a compressible fluid in a pipe with area variation, wall friction and heat transfer as shown in equ.2.1.

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} - a^2\left(\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x}\right) - (\mathbf{K}-\mathbf{1})\rho\,(q+uG) = \mathbf{0} \qquad (2.1)$$

Numerical Solution

Application of Galerkin's Finite Element Methods to equation (2.1). Nwaogazie, I.L. (2004).

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} - a^2\left(\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x}\right) - (\gamma-1)\,\rho(q + 2\xi u^3/D),,,,,,,,,,,,,,,,,,,,, \qquad (2.3)$$

The pressure terms in equation 2.1 can be written in terms of density using ideal gas equation.

$$PV = nRT \ldots\ldots\ldots\ldots \qquad (2.4)$$

$$P = \frac{m}{MV}RT \text{ or } P = \rho\frac{RT}{M}$$

At constant temperature.

$$\partial p = \frac{RT}{M}d\rho \ldots\ldots\ldots\ldots \qquad (2.5)$$

Substituting for ∂p in equation (2.3).

$$\frac{RT}{M}\frac{\partial \rho}{\partial t} + u\frac{RT}{M}\frac{\partial \rho}{\partial x} - a^2\left(\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x}\right) - K\rho = 0 \ldots\ldots\ldots\ldots \qquad (2.6)$$

where,

$$K = (\gamma-1)(\dot{q} + 2\xi u^3/D) \ldots\ldots\ldots\ldots \qquad (2.7)$$

Collecting like terms gives,

$$\left(\frac{RT}{M} - a^2\right)\frac{\partial \rho}{\partial t} + \left(u\frac{RT}{M} - a^2 u\right)\frac{\partial \rho}{\partial x} - K\rho = 0 \ldots\ldots\ldots\ldots \qquad (2.8)$$

Equation 2.8 can be written as

$$K_1\frac{\partial \rho}{\partial t} + K_2\frac{\partial \rho}{\partial x} - K\rho = 0$$

Using Galerkin`s Finite element method.

Appling Galerkins weighted redual method and using a linear element, the element equation are as follows,

$$K_1\frac{\partial \rho}{\partial t} = \frac{kL}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix}$$

$$K_2\frac{\partial \rho}{\partial x} = \frac{k}{2}\begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix}$$

$$K\rho = \frac{kL}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix}$$

Adding the above terms;

$$+\frac{k}{2}\begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix} + \frac{kL}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix} = 0$$

$$a^2 = \frac{\gamma p}{\rho} = \frac{\gamma R\,T}{M}$$

Assemblage of Element Equations Into Global Equations

The assembled of global matrix equation for Eq. (2.1) can assume the following general form:

$$[A]\{B\} + [E]\{B\} = \{F\}$$

In which [A] is the assemblage of the first matrix; [E] is obtained by the addition of the assemblage of the second, third and fourth matrices and [F] is the assemblage of the flux vector (or the fifth term), respectively. Because of the time derivation {B} there is need to carry out some form of approximation to the derivations to reduce the equation to system of algebratic equivalent before solving.

Approximation of Time Derivatives

The concept of extending the finite element to include the time domain the approach is to regard the basis or approxiamation function as being dependent on time as well as the domain . such that,

$$\frac{\partial B(x,l)}{\partial t} = \frac{\partial N_i(x,t)}{\partial t} B_i$$

where,

B(x,t) = dependent variable, B, expressed as a function of space , x and time, t; $N_i(x,t)$ = basis/approximation function at nodes, i, as a function of space and time.

Applying the finite element methods to the various parts of the exhaust flow system, Manifold, Catalytic converter, Muffler and Tail –pipe**.**

Exhaust Manifold

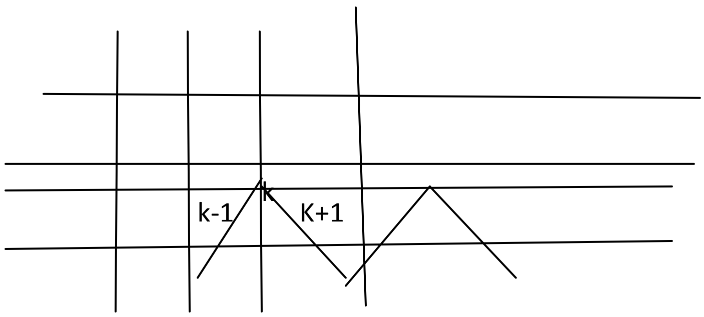

Figure 3.4: Discritized Exhaust Manifold

The following readings were taken from a four cylinder internal combustion engine exhaust in mechanical workshop at Petroleum Training Institute (PTI) Effurun.

Table 1: Properties of the fluid

1	Exhaust temperature	400 K
2	Velocity of flow	59.3 m/s
3	Molecular mass of air	29g/mol
4	Gamma γ	1.395
5	Universal gas constant	8.3143KJ/Kmol K
6	ξ	0.0005
7	$\dot{q} = 200w,$	
8	Diameter of the exhaust pipe D	$50x10^{-3}$m.

$K_1 = (\frac{RT}{M} - a^2) = (\frac{8.3143 \text{ x } 400}{29} - a^2)$

where,

$a^2 = \frac{\gamma p}{\rho} = \frac{\gamma R T}{M} = \frac{1.395 \text{ x } 8.3143 \text{ x } 400}{29} = 159.89$

$K_1 = (\frac{RT}{M} - a^2) = (\frac{8.3143 \text{ x } 400}{29} - \frac{1.395 \text{ x } 8.3143 \text{ x } 400}{29})$

$= - 45.2752.$

$K_2 = \frac{URT}{M} - a^2 U = U(\frac{RT}{M} - a^2)$

$= 59.3 (\frac{8.3143 \text{ x } 400}{29} - 159.89)$

$= - 2684.44$

$K = - (\gamma-1)(\dot{q} + 2\xi u^3/D)$

$= - (1.398 - 1)(200 + 2.0005 \text{ x } 59.3^3/50\text{x}10^{-3})$

$= - 1739.48$

Let L = 1, Δt = 5 sec, t = 60 sec.

Substituting the values of K and L in equation (3.56),

$$-\frac{45x1}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix} - \frac{2684}{2}\begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix} - \frac{1739.48}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix} = 0$$

Let,

$$A = -\frac{45x1}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix},$$

$\Delta t = 5$,
$\theta = 0.55$,

$$E = -\frac{2684}{2}\begin{bmatrix} -1 & 1 \\ -1 & 1 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix} - \frac{1739.48}{6}\begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}\begin{Bmatrix} \ell_1 \\ \ell_2 \end{Bmatrix}$$

Substituting the values of A, Δt, θ and E into equation (3.66)

$$[A + \Delta t \theta E]\{\ell\}^{K+1} = [A - \Delta t(1-\theta)E]\{\ell\}^{K} + \{F\}^{K}$$

$$-\frac{45}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}+5x0.55-\frac{2684}{2}\begin{bmatrix}-1 & 1\\ -1 & 1\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}-\frac{1739.48}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}^{K+1}=$$

$$-\frac{45}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}-5(1-0.55)-\frac{2684}{2}\begin{bmatrix}-1 & 1\\ -1 & 1\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}-\frac{1739.48}{6}\begin{bmatrix}2 & 1\\ 1 & 2\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}^{K}$$

Simplifying the above gives,

$$-\begin{bmatrix}15 & -7.5\\ -7.5 & -15\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}+\begin{bmatrix}52745 & -4482\\ 28985 & -52745\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}=$$

$$\begin{bmatrix}-15 & -7.5\\ -7.5 & -15\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}-\begin{bmatrix}43155 & -36675\\ 23715 & -43155\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}$$

Simplifying the matrix further gives,

$$\begin{bmatrix}52896 & -44895\\ 2991 & -52895\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}^{K+1}=\begin{bmatrix}-43005 & -3675\\ -2379 & -4330\end{bmatrix}\begin{Bmatrix}\ell_1\\ \ell_2\end{Bmatrix}^{K} \tag{3.78}$$

Equation (3.78) is solve using excel program for ten nodes and the values obtained are plotted. This was repeated for the Catalytic converter, Muffler and the Tail pipe.

Table 2: Shows Data Obtained For The Exhaust Manifold

		3.358	-3.36	-3.4	-3.4	6.72					
1	0	E-19	E-19	E-19	E-19	E-19	0	0	0	ρ1	1.9
-6.15	0.00	-0.001	0.001	-0.00	0.002	-0.004	0.00	-0.00	0.00		-11.
404	116	771	789	273	751	215	423	65	65	ρ2	693
-6.031	0.00	-0.002	0.002	-0.00	0.003	-0.004	0.00	-0.00	0.00		-11.
312	114	074	096	32	222	938	495	762	76	ρ3	459
-3.923	0.00	-0.00	0.001	-0.00	0.00	-0.002	0.00	-0.00	0.00		-7.4
916	074	135	138	174	175	682	269	414	41	ρ4	554
-3.858	0.00	-0.001	0.001	-0.00	0.002	-0.003	0.00	-0.00	0.00		-7.3
499	073	327	119	205	064	162	317	488	49	ρ5	311
-2.50	0.00	-0.00	0.000	-0.00	0.001	-0.001	0.00	-0.00	0.00		-4.7
187	047	086	726	133	114	707	171	263	26	ρ6	536
-2.468	0.00	-0.000	0.000	-0.00	0.001	-0.002	0.00	-0.00	0.00		-4.6
508	047	849	716	131	099	025	203	312	31	ρ7	902
-1.595	0.00	-0.000	0.000	-0.00	0.00	-0.001	0.00	-0.00	0.00		-3.0
126	03	549	463	085	071	309	109	168	17	ρ8	307
-1.579	0.00	-0.000	0.000	-0.00	0.000	-0.001	0.00		0.00		-3.0
284	03	543	458	084	703	296	108	-0.002	2	ρ9	006

-1.016 975	0.00 019	-0.00 035	0.000 295	-0.00 054	0.000 453	-0.000 834	0.00 069	-0.00 129	0.00 11	ρ10	-1.93 23

Results And Discussion

The Manifold

Node 1 corresponds to the first point in the manifold pipe, i.e., the pipe entry. Node 5 corresponds to the mid-point in the pipe. Node 10 corresponds to the outlet end of the manifold pipe. In this case it is assumed that one end of the pipe is open to a receiver and the other end is the outlet end. The result obtained using the excel program is presented in Table 4.1. And represented graphically in fig. 4.1 for the Manifold. Similarly fig. 4.4. through Fig.4.5.is for the Catalytic converter, the exhaust Muffler and the exhaust tail-pipe.

The density at the entry end of the pipe. is constant and is equal to 1.9. Since the pipe end is open to the atmosphere, the pressure does not change throughout the simulation time. At the pipe entry, the pressure decreases at first and then remains constant for a certain period of time and then decreases as the simulation time increases. At the midpoint, the wave action phenomenon increased pressure is reflected. The decreases and increases in pressure effect becomes small and smaller until the density gradually falls and reaches a constant value.

Fig.4.1. Shows the decrease in density of the exhaust gases with increase in distance towards the end of the manifold.

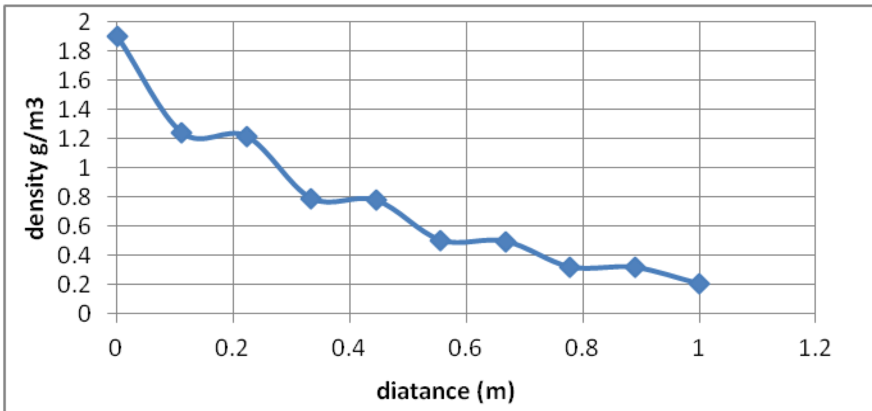

Fig 4.1 Density against distance for exhaust manifold.

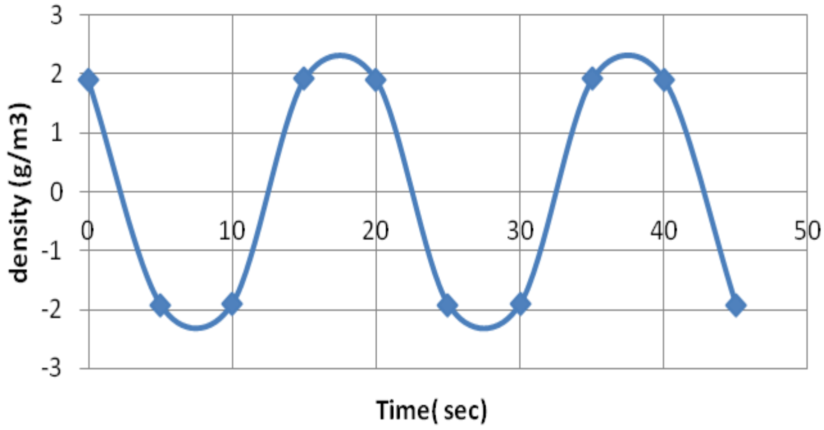

Fig4.4 Density against time for Catalytic converter.

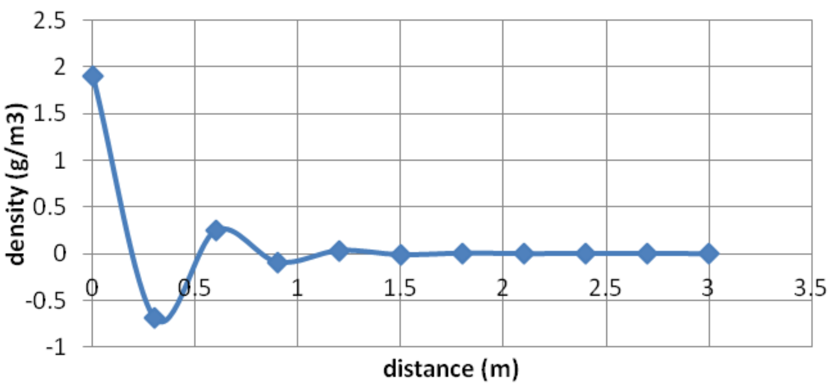

Fig.4.6 Densityagainst distance for exhaust muffler.

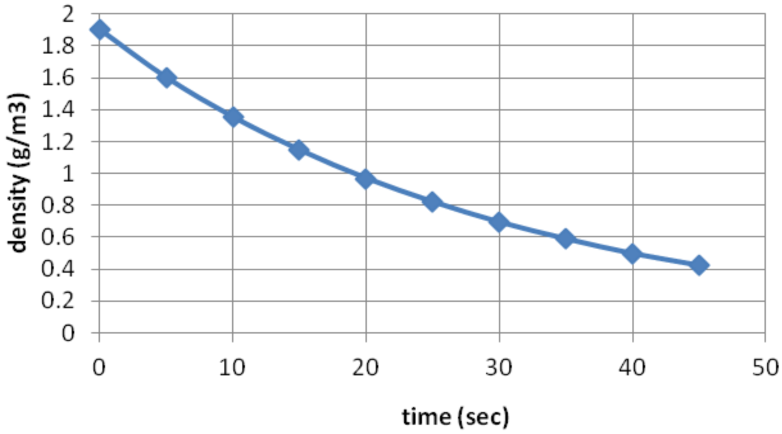

Fig 4.8 Density against time for Exhaust tail pipe.

Conclusion

The finite element method was used to simulate the fluid in an internal combustion engine.The differential equation obtained was solved using Galerkin`s finite element method.

The results obtained for each of the components were plotted as shown in Figures, 4.1 to 4.8.

This study may be used in the design of automobile exhaust system for control of noise, excessive heat and harmful gaseous emissions to the environment.

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