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TURBULENT FLOW AROUND CONCENTRIC CAPSULE TRAIN IN HYDRAULIC CAPSULE PIPELINE (HCP)

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ABSTRACT

The present work is concerned with practical aspects of modeling the turbulent flow around concentric capsule train in pipe. Turbulence model is the k-ε model. Firstly, the turbulence modeling was modified for the concentric capsule train without any intercapsule spaces in pipe to simulate the flow as axi-symmetric, two dimensional, steady flow with edge effects. Secondly, the turbulence modeling was established for the same case but with different equal and unequal intercapsule spaces. The main concept of this simulation is to study the effect of intercapsule space on capsule flow performance such as the total pressure drop, the drag coefficient, and the shape of the flow pattern. Finally, all of these models were verified not only by making a force analysis on the capsule train to check its balance but also by comparing their results of the friction factor with experimental data from the literature. The obtained results are in good agreement with the experimental data. The capsule train would be balanced (i.e. the net propelling pressure forces equal the drag resisting shear forces), so that this balancing should be applied for all cases. The overall pressure drop across the capsule train was shown to be decreased as increasing the intercapsule space. This leads to decrease the mass of the transported cargos because of decreasing the number of capsules for the same pipeline length so that the designing of capsule pipeline systems needs optimization for this intercapsule space.

KEYWORDS:

Capsule train pipeline, Turbulence modeling, Intercapsule space, concentric annulus.

INTRODUCTION

Hydraulic capsule pipeline (HCP) technology is the most versatile type of freight pipelines, capable of transporting almost any cargo, including solids and packaged products, of a size slightly smaller than the diameter of the pipe though which the cargo moves. The water is used both to suspend and to propel capsules through the pipeline. HCP travels at 1.8 to 3 m/s in pipe. HCP is more suitable for transporting bulk materials such as grain and other agricultural products, and municipal solid waste, which do not require high speed for delivery. The past studies done in the capsule pipeline are used to design the system where it is required to make an economical study on the system before construct it; the initial cost of this system is very high. The saving in the running cost must cover this initial cost. The Capsule pipeline systems are safer than any other transport systems. More advantages of Capsule pipeline systems are stated as the following:

1- Lowest cost for freight transport as compared with other transportation modes in many situations.
2- Public desire to reduce reliance on trucks and trains due to serious pollution and safety problems, and increased congestion of highways and streets.
3- Damage caused by trucks to highway infrastructure and the associated high maintenance cost of infrastructure.
4- Desire to have a reliable, weatherproof, around-the-clock cargo delivery system.
5- Free from cargo theft during transportation.
6- Advantage of underground pipelines from a land use standpoint.
7- Increased pollution and increased demand for freight transportation.
8- Improve the quality of life and enhances national security.

Because of all the previous stated advantages, the capsule pipeline was an interesting field to be researched so that there are many researches done to analyze and improve the performance of both hydraulic and pneumatic capsule pipeline.

There are a successful series of researches performed by the capsule pipeline research center (CPRC) at the University of Missouri-Columbia-U.S.A to develop various capsule pipeline technologies, including HCP, PCP and CLP, Liu [7]. Liu and Rhee [11] studied the behavior of non-uniform-density capsules theoretically and experimentally. Lenau and El-Bayya [4] presented a theoretical model for unsteady Hydraulic Capsule flow by using the method of characteristics. Cheng and Liu [3] studied the tilt of stationary capsule in pipe by presenting theoretical and experimental models for stationary capsule i.e. when a cylindrical capsule moved by a liquid flowing in a pipe is stopped by the presence of an obstacle or protrusion on the pipe floor, the capsule may tilt in the pipe. An experimental model for polymer drag reduction in HCP was done by Huang et al [29]. They investigated the effect of the polymer (Polyethylene oxide "trade named Polyox") additives on the capsule pipeline performance (the flow friction factor). An Overview on freight pipelines: current status and anticipated future use was done by Liu [9] in that the basic concept, specifications, history, classification, system components, system operation, economics, expected and obstacles to future use, method of capsules injection, advantages, disadvantages, and applications are explained for several types of the freight pipelines. See also Liu [9].

An experimental model to investigate a Heavy Solid Capsules Conveyed by Liquid in Horizontal Circular Pipe was done by Vlasak and Myska [23] in that they presented a dimensional analysis and took experimental data on heavy solid capsule flow to investigate the effect of carrier liquid velocity, capsule to pipe diameter ratio, and shape of capsule on capsule to liquid velocity ratio and pressure gradient in the capsule train in pipe. An extension for the previous research was done by Vlasak [22] to present an experimental investigation of capsules of anomalous shape conveyed by liquid in a pipe. The pumping of capsule flow was studied by Vlasak and Berman [24] where the capsule used in the HCP are solid bodies comparable in proportion with pipe diameter. Because capsules cannot pass through the ordinary used pumps, special procedure and/or equipment have to be used for their injection and pumping. In this research a general analysis of capsule pumping systems were done. In general, two basic ways of pumping in capsule pipelining could be distinguished.

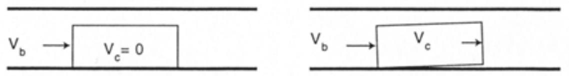
- The first way is based on separation of capsules and fluid and used a similar principle as slurry pipe hydrohoists or special bypass devices. It uses conventional centrifugal and reciprocal pumps. Its advantage is relatively high efficiency and possibility to work at high operational pressure. On the contrary, discontinuity of capsules movement and considerable space requirement has to be mentioned as draw-back.
- The second way pumps fluid-capsule mixture by specially developed kinds of pumps – reciprocating capsule pumps, annular axial flow or spiral capsule pumps, linear electric motors or special jet pumps designed for capsule-fluid mixture. Advantage of these pumps is continuous movement of capsules and relatively small demand on space.

An overview on capsule pipeline research at the Alberta research council, 1958-1978 was done by Brown [25]. This research is concerned on the HCP history, concept development, hydraulics, equipment development, system operation, and economics. Research and development in the technology then spread to other nations ASCE [27]. The Optimal design of a multi-stage capsule handling multi-phase pipeline was studied theoretically by Agarwal and Mishra [28]. Theoretical and Experimental models for drag coefficient of capsule inside a vertical angular pipe were performed by Yanaida and Tanaka [16].

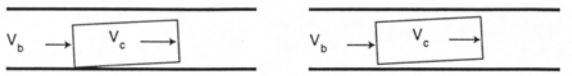
The coal log pipeline is the most important application on hydraulic capsule pipeline which had concentrated researches in the (CPRC). Li et al [30] studied the wall friction and lubrication during compaction of coal logs. Liu and Marrero [12] studied the coal log pipeline transportation of western coal. The coal log pipeline design and economics were studied and presented by Liu [8]. An extension for the previous research was studied by Liu et al [10] to present the economics of coal log pipeline for transporting coal. Liu and Marrero [13] presented an overview on coal log pipeline technology, hydrodynamics, Design program, effect of polymer additives (Drag reduction), unsteady capsule flow, wear of coal logs in pipe, coal log manufacturing, economics of the coal log pipeline and the status of development. The optimal moisture for rapid compaction of coal logs was studied by Gunnink and Li [2]. The wear of coal logs in pipe was studied by Merayyan and Liu [26]. They made an experimental setup to test the coal material wear as the coal circulated in the closed loop pipeline.

Other applications of the HCP flow are studied and researched by different researchers. Liu and Li [14] presented a feasibility analysis on transporting solid wastes by different pipelines (pneumatic, slurry, and capsule pipelines). The concentric flow regime of solid-liquid food suspensions was studied theoretically and experimentally by Barigou et al [18]. Pipeline transport and simultaneous saccharification of corn Stover was studied experimentally by Kumar et al [1]. The spherical capsules flow pressure drop was studied theoretically and experimentally by Ulusarslan and Teke [6].

As described by Liu [9], the motion of capsules in pipe can be classified into four regimes as shown in Figure 1. In Regime 1, the bulk fluid velocity, V_b is so low that insufficient drag is developed on the capsules to overcome the contact friction between them and the pipe in order for them to move. Regime 2 starts when the velocity of the fluid is high enough to cause the capsules to slide along the pipe. Further increase in fluid velocity beyond those in Regime 2 causes the flow to enter Regime 3, in which the capsule velocity overtakes the fluid velocity- Regime 3 ends when the fluid velocity is so high that the capsules are lifted off the pipe wall and become waterborne. Thereafter, the flow enters Regime 4.



(a) Regime 1 ($V_b < V_l$, $V_c = 0$) (b) Regime 2 ($V_l < V_b < V_L$, $V_c < V_b$)



(c) Regime 3 ($V_l < V_b < V_L$, $V_c > V_b$) (d) Regime 4 ($V_b > V_L$, $V_c > V_b$)

Figure 1 “Four regimes of Hydraulic Capsule Pipeline flow, Liu [9].”.

The present study is to model the turbulent flow around a lifted off concentric capsule train (Regimes 3 and 4) with different intercapsule spaces as two dimensional axi-symmetric flow around Capsules in Pipe considering the edges effect. The numerical solution is performed by not only solving the two momentum equations for turbulent flow (in [z] and [r] directions, i.e. in the flow and in the radial co-ordinates) to find the two components of velocity in the two direction of the flow (V_z and V_r) but also solving the continuity equation to check if the pressure gradient should be corrected or not to satisfy the continuity equation. A turbulence modeling is needed to solve the turbulent eddy viscosity which is the term established in the Reynolds Averaged Navier Stokes Equation (RANS) based on the Boussinesq approximation. One type of two equation models (k-ε model) is selected because Khalil et al [20] show that this model gives highly precise results. Khalil et al [20] simulate the turbulent flow around single concentric long capsule in a pipe by using different turbulence models. The present study is a continuation of the program which has started at the Mechanical Engineering Department, Alexandria University in cooperation with others since 2000. Another research developed from the same program is Khalil et al [19] to establish a numerical laminar annular flow model around a moving core in a pipe which is the first step of the present study. More details are given by Samaha [17].

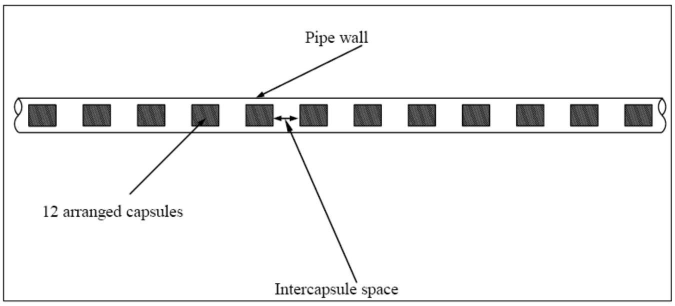


Figure 2 “Schematic illustration of capsule train in pipe.”.

The main purpose of the present simulation is to find the flow pattern shape, the pressure gradient along the capsule train shown in figure 2 and the friction factor at different intercapsule spaces to check the effect of increasing or decreasing these spaces on the drag coefficient and the pressure gradient. In addition, the obtained results are compared with the experimental data of Huang et al [29] to verify the model. Furthermore, a force analysis is performed on the capsule train to check the balance of the capsule train at the different intercapsule spaces.

PROBLEM DESCRIPTION

The present study includes the configurations shown in figure 2, a capsule train in concentric position in a pipe can be solved for assumed different intercapsule spaces such as (without any spaces, 0.125 L_{cap}, 0.25L_{cap}, 0.5 L_{cap}, L_{cap}, and unequal spaces). In addition, the present study contains solutions at different Reynolds number range from 41000 up to 113000 in pipe at capsule to pipe diameter ratios of 0.89 for capsule train consists of 12 capsules. These data were recommended by Huang et al [29] for practical capsule flow application. The pipe used in their experiment is 54 mm diameter.

Practically, in capsule pipeline, unless capsules are tied together it is impossible to have constant spacing between them when moving through pipe. It can be only talking about the average spacing between the individual capsules in a train. The average intercapsule spacing can be determined as follows:

$$\text{The average intercapsule spacing} = \frac{\text{Whole length of the pipeline - Capsule train length}}{\text{The number of capsules + 1}} \tag{1}$$

Where

The capsule train length = The number of capsules × The length of one capsule (2)

The present study is to solve the problem by assuming different average intercapsule spaces as shown in figure 3 after that check the balance of the capsule train by performing force analysis. Furthermore, check the validity of the model by comparing the obtained results of friction factor with that of the experimental data of Huang et al [29].

GENERAL CONSIDERATIONS

1. Incompressible Turbulent and steady flow.
2. Newtonian fluid.
3. The temperature and the fluid viscosity are assumed constant.
4. Axi-symmetric flow. Assume the center line of the capsule is coincided with the center line of the pipe.
5. Horizontal flow with no body forces.

The modeling of the turbulent eddy viscosity by using the Boussinesq approximation. One of the Two equations models (the standard k-ε).

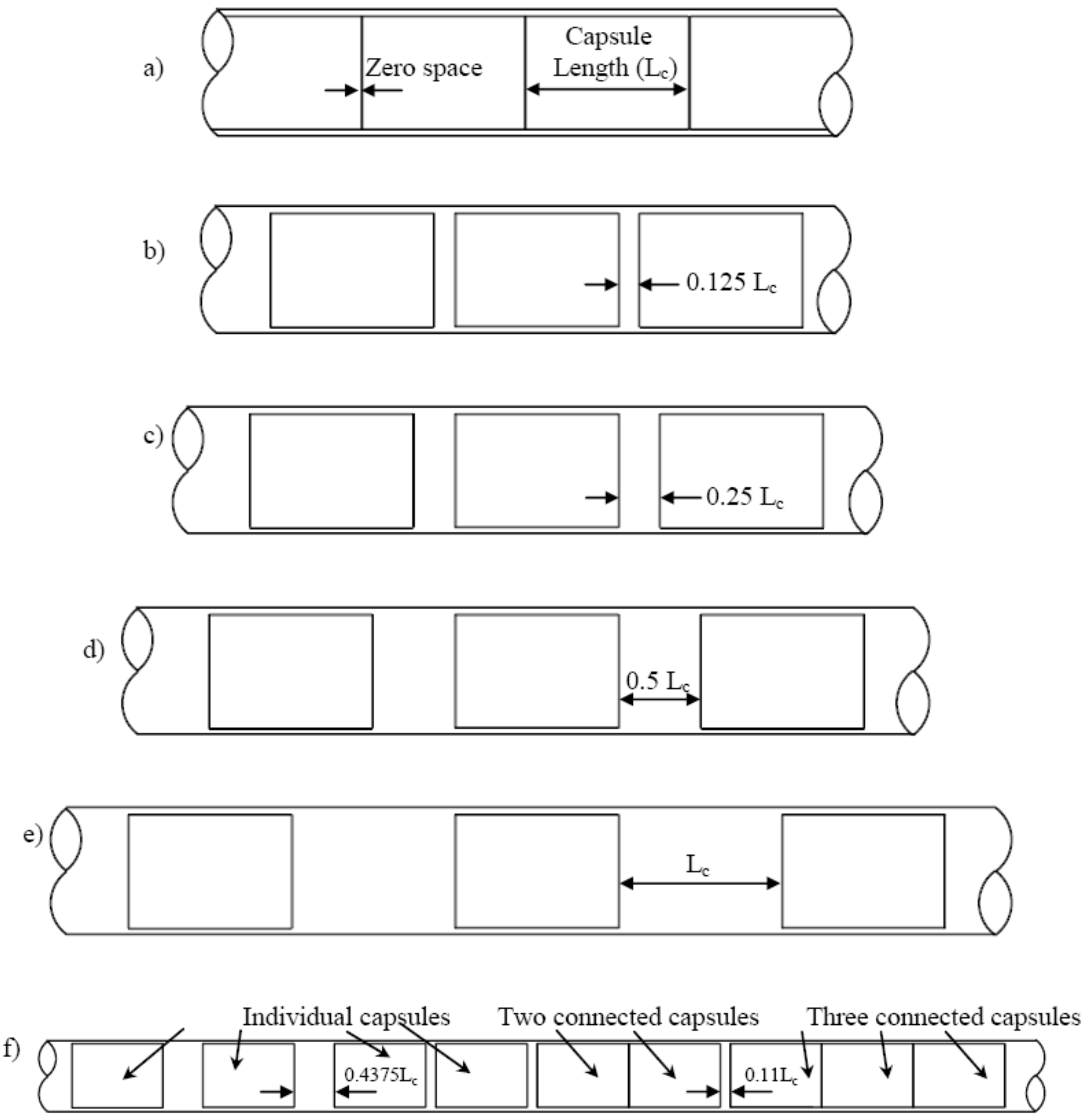


Figure 3 “Schematic illustration of capsule train with different intercapsules spaces
a- No spaces, b- space = $0.125L_c$, c- space = $0.25L_c$, d- space = $0.5L_c$, e- space = L_c, f- unequal spaces.”.

MESHING AND GRID GENERATION

In order to numerically solve the governing partial differential equations (PDEs) of the fluid flow around the capsule train, approximations to the partial differential equations are introduced. These approximations convert the partial derivatives to finite difference expressions, which are used to rewrite the (PDEs) as algebraic equations. The approximate algebraic equations, referred to as finite difference equations (FDEs), are subsequently solved at discrete points within the domain of interest. Therefore, a set of grid points within the domain, as well as the boundaries of the domain, must be specified. The creation of such a grid system is required to solve the problem. The multi blocks system grid generation is used in the present study where there is a sudden change in the flow direction (from pipe area to annulus area between the capsule and the pipe and then expansion to the pipe area again). Not only the meshing in the pipe area before and after the capsule but also the meshing in the annulus area is performed individually. For a physical domain enclosed by solid surfaces (i.e. capsule or pipe wall), clustering must be considered where large gradients of the flow properties are concentrated enclosed to the solid surfaces (Anderson [15]). In the present study, start to mesh the grid for the problem without any intercapsules spaces for the half of the domain (where the problem is axi-symmetric then solve the problem with some spaces (such as L_{cap}, 0.5 L_{cap}, 0.25 L_{cap}, 0.125 L_{cap}, and unequal spaces). The used grid is shown in figure 4.

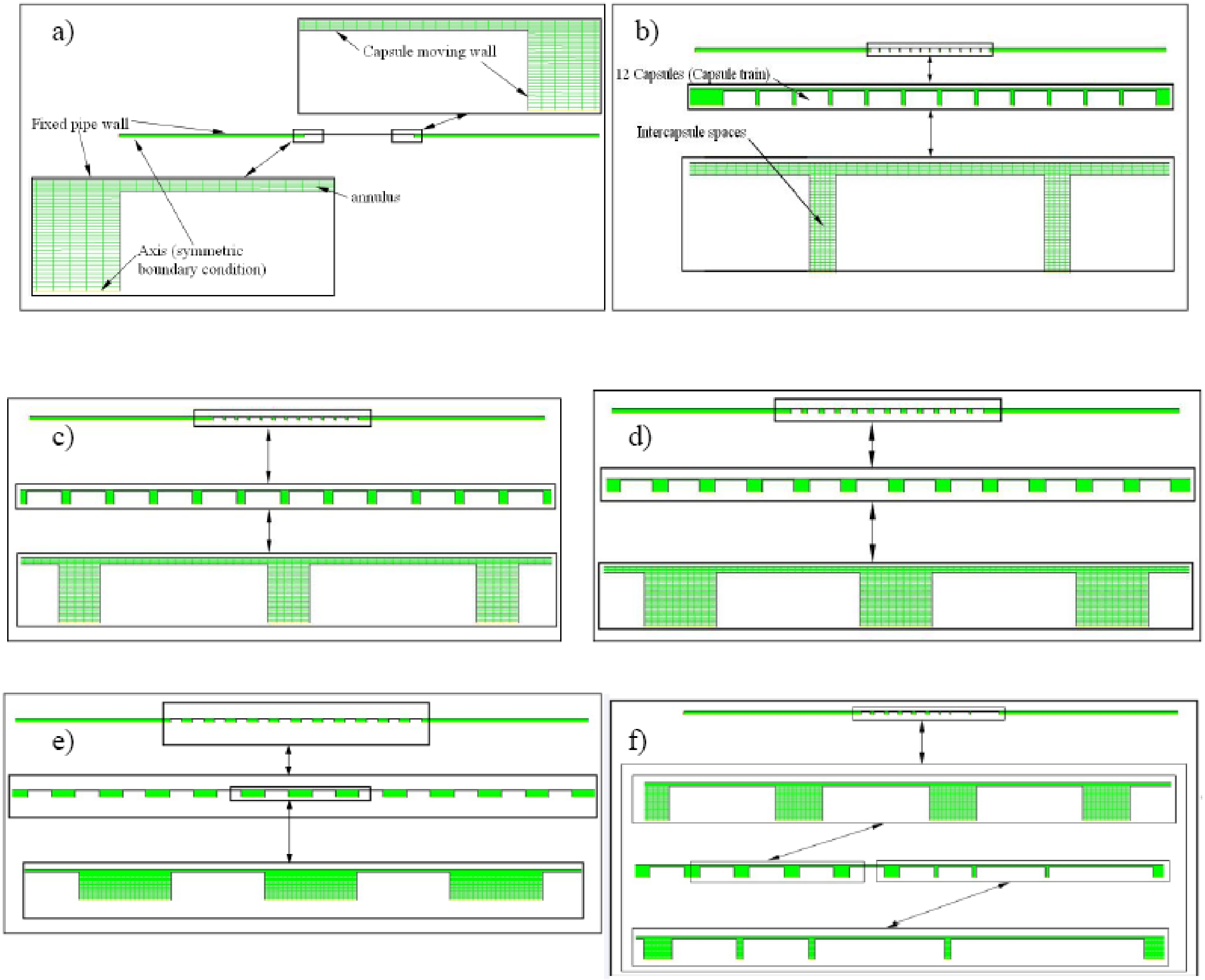


Figure 4 “The grid used to solve the capsule train with different intercapsules spaces
a- No spaces, b- space = 0.125L$_c$, c- space = 0.25L$_c$, d- space = 0.5L$_c$, e- space = L$_c$, and f- unequal spaces.”.

GOVERNING EQUATIONS

The governing equations to solve the two dimensional axi-symmetric turbulent flow are the momentum equation in the flow direction (in z-direction) and in the radial direction (in r-direction) to obtain their velocities. There is also two unknown terms in the momentum equations that are the pressure gradient and the turbulent eddy viscosity. The pressure gradient term can be estimated by assuming it then correct it until the continuity equation satisfied (Pressure correction technique). The turbulent eddy viscosity needs to turbulence modeling to be estimated.

Momentum equation in r-direction

$$\rho\left(\frac{\partial V_r}{\partial t}+\frac{\partial V_z V_r}{\partial z}+\frac{\partial V_r^2}{\partial r}+\frac{V_r^2}{r}\right)=\left[(\mu+\mu_t)\left(\frac{\partial^2 V_r}{\partial r^2}+\frac{1}{r}\frac{\partial V_r}{\partial r}\right)+\frac{\partial(\mu+\mu_t)}{\partial r}\frac{\partial V_r}{\partial r}\right]$$
$$-(\mu+\mu_t)\frac{V_r}{r^2}+(\mu+\mu_t)\frac{\partial^2 V_r}{\partial z^2}+\frac{\partial(\mu+\mu_t)}{\partial z}\frac{\partial V_r}{\partial z} \quad (3)$$

Momentum equation in z-direction

$$\rho\left(\frac{\partial V_z}{\partial t}+\frac{\partial V_z V_r}{\partial r}+\frac{\partial V_z^2}{\partial z}+\frac{V_z V_r}{r}\right)=-\frac{\partial P}{\partial z}+\left[(\mu+\mu_t)\left(\frac{\partial^2 V_z}{\partial r^2}+\frac{1}{r}\frac{\partial V_z}{\partial r}\right)+\frac{\partial(\mu+\mu_t)}{\partial r}\frac{\partial V_z}{\partial r}\right]$$
$$+(\mu+\mu_t)\frac{\partial^2 V_z}{\partial z^2}+\frac{\partial(\mu+\mu_t)}{\partial z}\frac{\partial V_z}{\partial z} \quad (4)$$

Continuity equation:

$$\left(\frac{V_r}{r}+\frac{\partial V_r}{\partial r}+\frac{\partial V_z}{\partial z}\right)=0 \qquad (5)$$

TURBULENCE MODELING

Two equation models

The simplest "complete models" of turbulence are two-equation models in which the solution of two separate transport equations allows the turbulent velocity and length scales to be independently determined. The Standard k-ε Model used in the present study falls within this class of turbulence model and has become the workhorse of practical engineering flow calculations in the time since it was proposed by Launder and Spalding, Wilcox [5], (equations from 6 to 9).

- **The Standard k- ε model**

-Turbulent viscosity

$$\mu_t = \rho C_\mu k^2/\varepsilon \qquad (6)$$

-Turbulence kinetic energy

$$\frac{\partial k}{\partial t}+V_z\frac{\partial k}{\partial z}+V_r\frac{\partial k}{\partial r}=\tau\left[\frac{\partial V_z}{\partial r}+\frac{\partial V_r}{\partial z}\right]-\varepsilon$$

$$+\frac{\partial}{\partial z}\left[(\nu+\nu_t/\sigma_k)\frac{\partial k}{\partial z}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r(\nu+\nu_t/\sigma_k)\frac{\partial k}{\partial r}\right] \qquad (7)$$

-Dissipation rate

$$\frac{\partial \varepsilon}{\partial t}+V_z\frac{\partial \varepsilon}{\partial z}+V_r\frac{\partial \varepsilon}{\partial r}=C_{\varepsilon 1}\frac{\varepsilon}{k}\tau\left[\frac{\partial V_z}{\partial r}+\frac{\partial V_r}{\partial z}\right]-C_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

$$+\frac{\partial}{\partial z}\left[(\nu+\nu_t/\sigma_\varepsilon)\frac{\partial \varepsilon}{\partial z}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r(\nu+\nu_t/\sigma_\varepsilon)\frac{\partial \varepsilon}{\partial r}\right] \qquad (8)$$

Closure Coefficients and auxiliary relations

$$\tau=\mu_t\left[\frac{\partial V_z}{\partial r}+\frac{\partial V_z}{\partial z}\right] \qquad (9)$$

$C_{\varepsilon 2} = 1.92$ $C_{\varepsilon 1} = 1.44$ $C_\mu = 0.09$ $\sigma_k = 1$ $\sigma_\varepsilon = 1.3$ (Wilcox [5]).

BOUNDARY CONDITIONS

Surface Boundary Conditions (Wall Functions)

Near Wall treatment for Two Equation Models is needed to complete the solution. For computations of wall-bounded turbulent flows, wall functions based on the law-of-the-wall and related hypotheses have long been used as economical, robust, and reasonably accurate means of treating the near-wall region. The so called "universal" law-of-the-wall representing the logarithmic mean velocity profile in the fully-turbulent region of the inner layer.

The velocity at the point next to the capsule wall

$$V_{zi}=V_c-U_{ti}\left[\frac{1}{\kappa}\ln\left(\frac{U_{ti}y}{\nu}\right)+C-1.13\left(\frac{U_{ti}y}{\nu}\right)\frac{\nu}{\rho U_{ti}^3}\frac{\partial P}{\partial z}\right] \qquad (10)$$

where C = 5.0

Note that it is required to subtract the logarithmic law of the wall from the capsule velocity to obtain the relative velocity where the wall is run with the capsule velocity).

The velocity at the point next the Pipe wall

$$V_{zo}=U_{to}\left[\frac{1}{\kappa}\ln\left(\frac{U_{to}y}{\nu}\right)+C-1.13\left(\frac{U_{to}y}{\nu}\right)\frac{\nu}{\rho U_{to}^3}\frac{\partial P}{\partial z}\right] \qquad (11)$$

For k-ε model the boundary will be:

$$k=\frac{U_t^2}{\sqrt{\beta_o^*}} \qquad (12)$$

$$\varepsilon=(\beta_o^*)^{3/4}\frac{k^{3/2}}{\kappa y} \qquad (13)$$

Turbulence parameters are calculated from their boundary equations explained as

k is calculated from:

$$\left[\frac{\partial k}{\partial r}=0\right] \qquad (14)$$

The production term of k is computed from

$$P_k \approx \tau_w\frac{\partial V_z}{\partial r} \qquad (15)$$

The inlet boundary conditions

The inlet boundary condition is uniform flow so that the relations given below used in the present work are those proposed by Spalding [21].

$k_{inlet} = C_k V_a^2$ where V_a is uniform, $C_k = 0.003$ (16)

$\varepsilon_{inlet} = C_\mu k_{inlet}^{3/2} / [(R_o-R_i) C_\varepsilon]$ where $C_\varepsilon = 0.03$ (17)

RESULTS AND DISCUSSIONS

The turbulence model (Using the commercial code FLUENT) is run by initializing the solution as uniform and allowing 0.0001 residual for all model parameters. Then allow the program to iterate until reach the converging solution as shown in figure 5. Note that the other cases of intercapsule spaces the converging solution is approximately as that of no spaces shown in Fig 5 so that no need to display them.

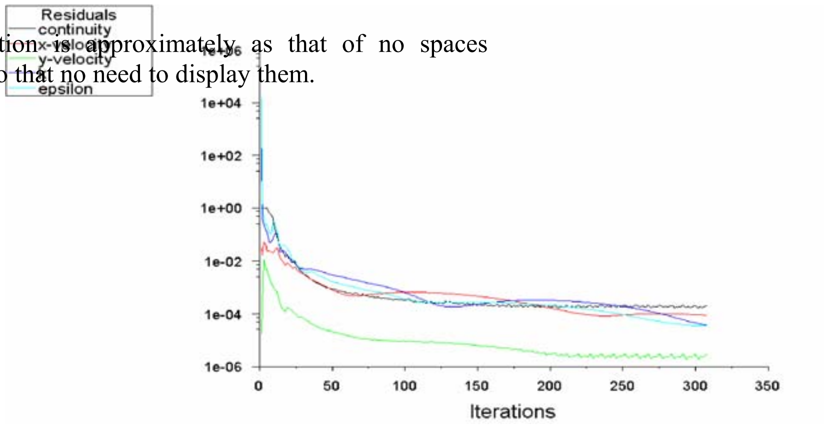
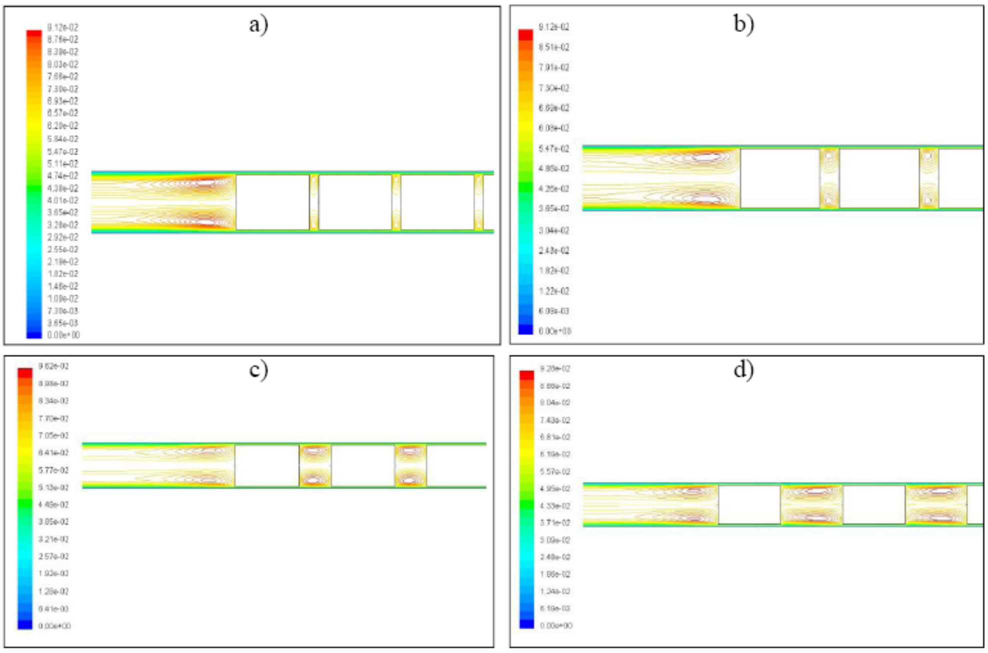
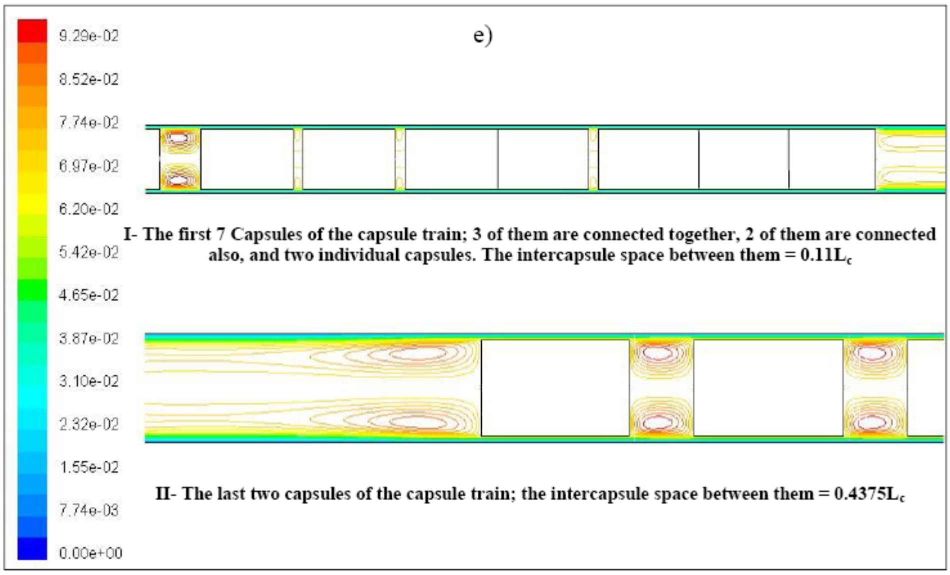


Figure 5 “converging solution for capsule train without any intercapsule space.”.





I- The first 7 Capsules of the capsule train; 3 of them are connected together, 2 of them are connected also, and two individual capsules. The intercapsule space between them = 0.11L$_c$

II- The last two capsules of the capsule train; the intercapsule space between them = 0.4375L$_c$

Figure 6 “Streamlines for Capsule train with different spaces.”.
a - space = 0.125L_c, b- space = 0.25L_c, c- space = 0.5L_c, d- space = L_c, e- unequal spaces

Figure 6 illustrates the flow stream lines for different intercapsule spaces. It is apparant that for capsule train without any spaces, the vortices doesn't appeared except at the capsule tail. For intercapsule space equal to 0.125 of capsule length, Figure (6-a), the vortices start to appear at each capsule tail and the fluid expands. As the spaces are increased (0.25L_c, 0.5L_c and L_c), the fluid expansion is increased and the vortices volumes are increased as shown in figures 6-(b, c and d). Figure (6-f) shows the flow stream line for the case of unequal spaces with different vortices volume and flow streams expansion.

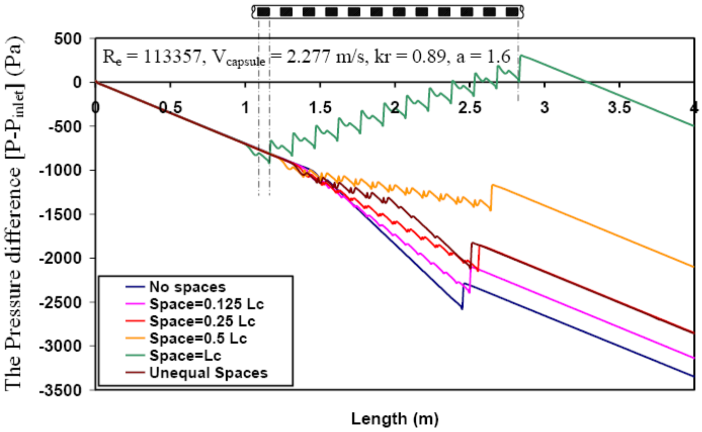


Figure 7 “the pressure distribution for different intercapsule spaces at the same Reynolds number.”.

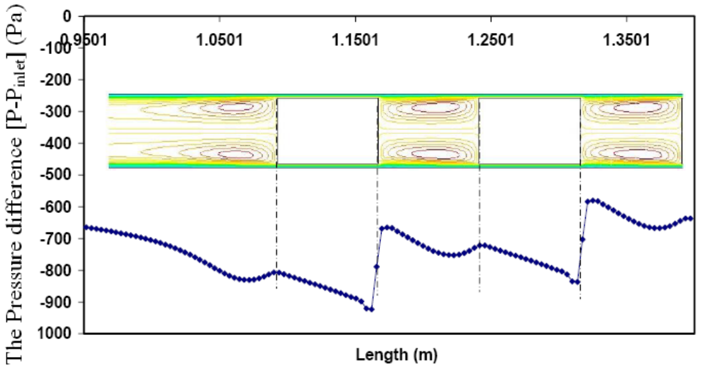


Figure 8 “the pressure distribution in comparison with the flow stream lines for intercapsule space = L_c, Focusing on the last two capsules.”.

Figure 7 shows the pressure distribution for different intercapsule spaces at Reynolds number R_e = 113357, $V_{capsule}$ = 2.277 m/s, diameter ratio kr = 0.89, and aspect ratio a = 1.6. The pressure gradient is affected by these intercapsule spaces. It is obvious that for capsule train without any spaces, there is no flow expansion except at the front of the first capsule so that the pressure is suddenly increased at that location. For intercapsule space equal to 0.125 of capsule length, the flow starts to expand at each intercapsule space from the annular area to the pipe area and those results in suddenly increasing in pressure from annulus to pipe. The increase in this case isn't high because the flow is reconverged from the pipe area to the annular area and that off course, reduces the pressure. As the spaces are increased (0.25L_c, 0.5L_c and L_c), the fluid expansion is increased and that results in increasing in the pressure at each intercapsule space and a small reduction in the pressure due to the presence of the vortices. Figure 7 shows also the pressure distribution for the case of unequal spaces with different flow expansion. Figure 8 focuses on the last two capsules of the train for intercapsule space = L_c. The pressure drop in the pipe, the intercapsule space, and the annulus are shown with comparison with the flow stream line vortices generation.

From the previous explanation, it is clear that as the intercapsule spaces are increased, the total pressure drop is decreased and that off course, results from the recurrence of the flow expansion which leads to the recurrence of the pressure increase at each intercapsule space. Increasing the intercapsule space may result in gaining pressure and power but it is illogic and needs to explanation.

To explain that, let's perform a force analysis on each capsule train with different intercapsule spaces to check their balance. By referring to figure 9, it is clear that each capsule is subjected not only to pressure difference (P_1 is applied at its tail cross section and P_2 is applied at its front cross section) but also to shear stress applied around its lateral area. For capsule motion with constant velocity, it should be balanced (the pressure differencing force is equal to the shearing force).

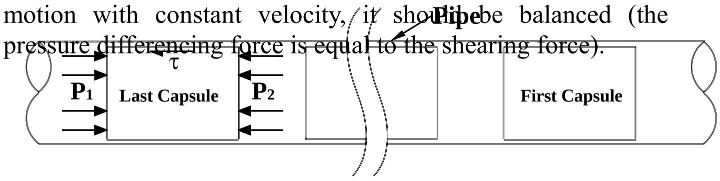


Figure 9 “Pressure and shear stress forces analysis on capsule train.”.

By analyzing pressure distribution results shown in figure 7, it is obvious that for capsule train without intercapsule spaces, the capsule train is unbalanced where the pressure force is higher than the shearing stress force. For capsule train with 0.125L_c and 0.25L_c intercapsule spaces, the capsule train is unbalanced where the pressure force is higher than the shearing stress force for all capsules except the first capsule at the front of the capsule train, the pressure force applied on it is on the opposite direction of the capsule velocity where the flow is expanded at this location and the pressure is suddenly increased.

For capsule train with 0.5L_c and 1.0L_c intercapsule spaces, the capsule train is unbalanced where the pressure force is lower than the shearing stress force for all capsules where the intercapsule space is high enough to expand the flow and increase the pressure.

To find an arrangement for capsules of the capsule train which satisfies the balance for the capsules in the capsule train, we should do the following: first, find an intercapsule space by trying and error for capsules which satisfies the balance for them irrespect of the first few capsules of the train (the space was found to be 0.4375 L_c). Second, try to reach an arrangement for the first few capsules which should be connected together to overcome the high increase of the pressure at the front of the first capsule. The arrangement was found (by trying and error) to be: a group of 3 connected capsules at the front of the capsule train; this group should be with intercapsule space of 0.11L_c with the next group which is of 2 connected capsules; this group should be with intercapsule space of 0.11L_c with an individual capsule which should be with intercapsule space of 0.11L_c with another individual capsule. This is the arrange of the first 7 capsules. The remaining 5 capsules should be with intercapsule space of 0.4375L_c with each other. This arrangement is found by trying and error to satisfy the balance for the capsule train. This arrangement is shown in figure (3-f). The pressure distribution for this arrangement is shown in figure 7 which give a total pressure drop equal to that given from 0.25 L_c intercapsule space but the later arrangement is unbalanced.

To verify all of the previous presented cases of the turbulent model, it should compare the Darcy-Weisbach friction factors obtained by the turbulent model with that obtained experimentally by Huang et al. [29]. Figure 10 illustrates the friction factors plotted experimentally as a function of Reynolds for water flow, capsule flow (a=1.6, kr=0.89, S=1.33), and capsule flow (a=3.23, kr=0.77, S=1.14). From figure 10 it shows that the capsule train model with the intercapsule spaces of 0.25 L_c and unequal intercapsule space are the nearest to the experimental data and is better than the model of no spaces and 0.125 L_c space. The model results with 0.5L_c and 1.0 L_c aren't plotted in figure 10 because they give negative friction factor (opposite pressure direction) which is illogic so that their results aren't plotted.

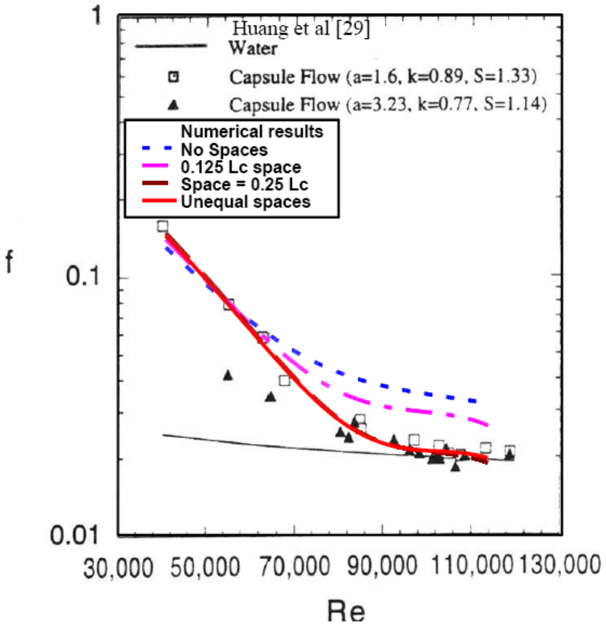


Figure 10 “Comparison between the numerical models with the experimental data of Huang et al [29].”.

CONCLUSIONS

The present study of the Turbulent flow provides two dimensional, axi-symmetric, steady model to predict the flow properties in concentric annulus and the intercapsule spaces for capsule trains and to study the effect of changing the intercapsule spaces on the flow properties. From this study, it is clear that:

1. As the spaces are increased both the fluid expansion increased and the vortices volumes increased and that results in the total pressure drop is decreased because the intercapsule spaces become high enough for the flow expansion which allow the pressure to be recovered.

2. The recurrence of the flow expansion leads to the recurrence of the pressure increase at each intercapsule space.

3. As the spaces are increased the total pressure drop is reduced and that saves the pump power required to propel the capsules but that reduces the quantity of cargos required to be transported where the total number of capsules along the line is reduced.

The models are verified by comparing their results with experimental data of other investigations and it gives a good agreement with them along a wide range of Reynolds numbers and the recommended diameter ratios. These result in ensuring the validity of the used equations, finite difference scheme, Turbulence modeling and the solving technique.

NOMENCLATURE

SYMBOL

a	The capsule aspect ratio (Capsule length/Capsule diameter).
C_d	Drag Coefficient.
d_c	Capsule diameter (m).
d	diameter
h	Annular space (m).
k	Turbulence kinetic energy (m^2/s^2).
kr	Capsule to pipe diameter ratio.
L_c	Capsule length (m).
P	Pressure (Pa).
$\frac{\partial P}{\partial z}$	Pressure gradient (Pa/m).
Q	The flowrate (m^3/s).
r	Radius at any point (m).
r_i	Inner radius of annulus (m).
r_o	Outer radius of annulus (m).
Re	Reynolds number, $[\rho V_b d_o/\mu]$.
S_{ij}	Strain rate (1/s).
S	Capsule specific gravity.
U_t	Friction velocity (m/s).
V	Any velocity (m/s).
y	The normal distance from the wall (m).
z	Any longitudinal length in axial direction.
$-\rho\overline{u_j^{/}u_i^{/}}$	Reynolds stresses (Pa).

GREEK SYMBOL

ε	Dissipation rate (m^2/s^3).
ψ	Stream function (kg/s).
ρ	Fluid density (kg/m^3).
μ	Fluid viscosity (Pa/s).
μ_t	Turbulent eddy viscosity (Pa/s).
τ_w	The wall shear stress.
Σ	Summation.
ν	Fluid kinematic viscosity (m^2/s)
κ	von Karmen constant.

SUBSCRIPTS

t	Turbulent.
z	Axial co-ordinate.
r	Radial co-ordinate.
c	Capsule.
b	Bulk.
a	Annular.
R	Reference.
o	outer

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