A COMPUTATIONAL STUDY OF INTERFACIAL MIXING IN PIPEINES, LOGISTICS AND DIVERSE MODELS TO PREDICT THE INTERFACE LENGTH

By

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Abstract:

Oil and gas are important resources of the U.S economy. Pipelines are the primary means of transporting oil and gas in the United States. Different grades of petroleum products are sent in the same pipeline as it is cost effective, which is known as batching. While two or more fluids are sent as a batch, mixing occurs at the interface of the two products known as "Transmix". Transmix varies in length and time across the length of the pipeline. Most of the study was done on developing the equation for the interface length and the factors influencing it. Factors influencing the transmix volume are pipeline length, pipe diameter, Reynolds number, kinematic viscosity of the mixture, mean flow velocity, friction factor, the type of flow regime and relative roughness factors. Software was developed to calculate the volume of the transmix and to predict how the above factors influence the transmix length. It was also observed that the elbows and bends increase the transmix length as the interfacial mixing occurs near the bends in the pipeline. Reducing the axial dispersion lessens the mixing in the pipeline which in turn reduces the transmix volume which is cost efficient to the oil and gas industry, as less product is sent for re-refining.

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NOMENCLATURE

A	Cross-sectional area of the pipe
C	Mean concentration (moles/l)
C_0	Initial concentration
D	Coefficient of molecular diffusion (m^2/s)
d	Diameter (m)
e	number of Elbows
F	Friction factor
K	Axial Dispersion coefficient (m^2/s)
K_L	Loss coefficient
$K_{L,elbows}$	Loss coefficient for elbows
$K_{L,union}$	Loss coefficient for Union, Threaded
$K_{L,tees}$	Loss coefficient for Tees
$K_{L,valves}$	Loss coefficient for Valves

K_T	Coefficient of diffusion
L	Length of the pipe
l_e	Equivalent length of the pipe
M	Mass (Kg)
p	Pressure (bar)
Q	Volumetric flow rate
r	Radius (m)
Re	Reynolds number
S	Interface length
t	number of Tees
T	Time
U	Mean speed of the flow (m/s)
u_0	Maximum velocity at the center of the pipe (m/s)
U_{max}	Average velocity
u	number of Union, Threaded
v	number of Valves
V	Average velocity

υ_{Blend} Viscosity of Transmix

VBN_{Blend} Viscosity Blending Number

VBN_A Viscosity blending number of component A

VBN_B Viscosity blending number of component B

$V_{Interface}$ Volume of the Interface

x_A Mass fraction of component A

x_B Mass fraction of component B

Greek Letters:

$\tau(r)$ Tangential stress

ρ Density (Kg/m^3)

μ Dynamic viscosity

υ Kinematic viscosity

η Boltzmann constant

ε Absolute Roughness factor

CHAPTER I

INTRODUCTION

Oil and natural gas are important resources of the U.S economy, accounting for more than 65 percent of the energy consumed in the United States. In the US more than 6000 natural gas producers exist ranging from small companies to major energy producers and has over 550 processing plants producing nearly 15 trillion cubic feet of natural gas a year. The natural gas that is produced in these plants is distributed through the natural gas pipeline network which runs across the country for about 300,000 miles. About 148 billion cubic feet of natural gas is carried through the pipelines from the place where it is produced to the place where it is used every day.

The pipelines are used for transporting crude petroleum and refined petroleum over long distances. More than 180,000 miles of liquid petroleum pipelines traverse the United States. Crude oil is moved from the production site to refineries and from there to the consumers. These movements take place using transportation by different modes. Barges and tankers are used to transport crude oil and refined products across the water while pipelines, trucks or trains are used for the transportation of crude oil on the land.

Pipelines are the most efficient method for the transporting of crude oil and refined products. Nearly two-thirds of the oil and petroleum products are transported by pipelines and are by far, America's most significant petroleum supply line, including crude oil, refined fuel and raw materials. Most of the pipelines that are used today are manufactured according to the specifications of American Petroleum Institute (API). The pipe size depends on the volume of the product that has to be transported from the facility to the refinery or to the consumer where it is used. It varies from 2 in. to 60 in. in diameter depending on the system and the throughput required. According to API, the pipelines range in a size of about 2 in. to 60 in. in OD; gathering systems range from 4 in. to 12 in. in diameter and the transmission lines ranging up to 56 in. in diameter. When a small diameter pipe is used for transporting it requires to be operated at high pressures and more compression power is required, which is not economical. This increases the capital costs as well as the operating costs. So, a pipe with larger diameter at lower operating pressures decreases the capital costs increasing the safety of pipeline. A pipeline design having low pressures and compression power is used, as it eliminates the need for the high pressure valves and has a lower installation cost compared to the alternative cost which is more expensive to operate. Pipelines are safe and efficient as most are buried and are unseen. In addition to their efficiency, pipelines also have important environmental and safety benefits.

Pipeline Logistics

Crude oil, collected from the field gathering systems is moved to storage tanks where the oil is measured and tested. The crude oil that has been collected from the gathering systems is sent to a pump station where the oil is delivered to the pipeline, having delivery and collection points along the route. Pressure is maintained in the pipelines with the help of booster pumps and compressors which keeps the oil flowing. Today, technology allows for the manufacture of large diameter and more efficient pipeline systems and pump stations that are primarily driven by clean electrical power. A huge quantity of petroleum in the pipeline moves through highly automated systems which has been a major factor in reducing the number and volume of pipeline spills. These automated systems allow the operators to monitor rates of flow, pressures and fluid characteristics. The operators are alerted and the pipelines are shutdown in case of potential leaks.

Product pipelines ship gasoline and diesel fuel from the refinery to the distribution facilities. In the refineries crude oil is converted into fuel and other products, from here it is sent to terminals where fuels are transported to retail outlets. The pipelines connect the producing areas to refineries and chemical plants while delivering products, the consumers need. Pipelines operate throughout the year. A pipeline may handle several types of crude oil and is scheduled in such a way that the right crude oil is sent to the respective destination. Crude oil moves in more than one pipeline system as it travels from the oil field to the refinery. To ensure smooth and continuous pipeline operation storage systems are located along the pipeline. After the crude oil is converted into refined products such as gasoline, pipelines are used to transport these products to terminals for transporting it to the gasoline stations. Product pipelines are used in shipping of various products in addition to gasoline. As, many product pipelines are used to move different products, these products are shipped in the pipelines in batches. Delivery points may be refineries, where the oil is processed into products, or shipping terminals, where the oil is loaded onto tankers.

Batching is a process where different grades of products are transported through the same pipeline. The products are transported in a series of batches and are mixed with the adjoining batches where they come into contact. This mixture of refined products while transporting in pipelines is called **transmix** or **contamination length**. As a variety of refined products move through the same pipeline, some mixing occurs where the trailing end of a batch of one product meets the leading edge of the next batch in the pipeline. The contamination length or transmix is the blended product that varies with concentration and which increases while moving downstream.

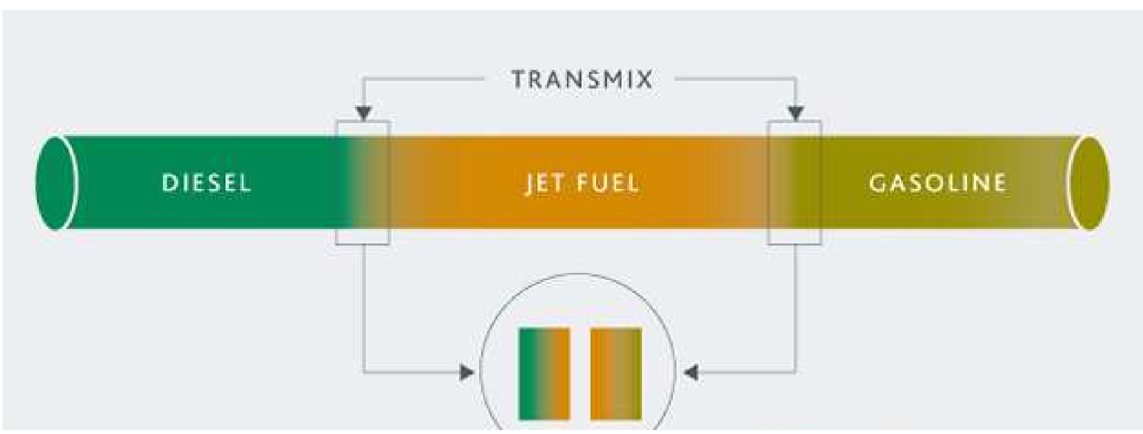


Fig 1.1 Interface of two fluids (From alliedenergycorp.com)

Even though the contamination length is very short in the pipeline in which the products are batched, it is of utmost importance that the purity of each product is maintained. A physical barrier might be used to separate the products in the batching process. The difference in density of the two products maintains the separation in the batching process when a physical barrier is not present and when the contamination length is very small. The extent of mixing and the position of each batch are monitored by measuring the density at a particular point. Sophisticated monitoring and control is required to monitor movement when more than one product is in the pipeline. Product pipelines are also operated at higher pressures than the crude oil as the material being transported is lighter than the crude oil.

Many product pipelines have standard product specifications. If two similar products containing different grades of gasoline are transported in batches, the interface can be incorporated into the lower-grade product. When two dissimilar products come into contact, the mixed product is called transmix, which is collected separately, and then trucked back to a refinery for reprocessing. This mixed stream may be sent back to a refinery for re-refining, sold as a lower valued product or sold as a mixture.

Some disadvantages of pipelines are that they can be easily damaged, require significant capital cost and time to build, and are less flexible. Geopolitical problems can be very significant when a pipeline crosses a number of countries. The major disadvantage of the pipelines which is of major concern is the transmix that requires the product to be sent back for re-refining which increases the product cost per gallon and also the transportation costs to and from the refinery.

The wall thickness also plays a major role in the design calculations and in the contamination length. When a pipeline passes through a corrosive soil environment at a given operating pressure a pipeline with greater wall thickness is required. Coating and wrapping the exterior of pipelines is one of the economical ways to extend the life of the pipeline. Coating is used to resist corrosion that damages the pipeline.

Physical properties of the fluids flowing in the pipeline also affect the contamination length. Some of the parameters which affect the contamination length are pipe diameter, pipe length, specific density, temperature, viscosity, vapour pressure, Reynolds number and friction factor.

Scope of this study:

Taylor's (1954) equations can be used at various Reynolds numbers in the laminar flow regime but do not predict accurately for the turbulent flow regime. A study will be done on how the equations can be modified to accurately predict the turbulent flow regime. This study mainly focuses on the development of the software for calculating the interface length. Sensitivity analysis was done on the parameters such as pipe length, pipe diameter, average velocity of flow in the pipe, viscosity and mass fractions of the fluids.

The study will also include the effects that the pipe bends and elbows have on the axial dispersion. Elbows are used to connect the pipelines of short length and to change the direction of the flow in the pipeline. It is observed that the presence of bends and elbows increases the axial dispersion when compared to that of a straight pipe. The Reynolds number also has a significant effect on length of interface. In this study we can examine how the bends affect the axial dispersion and length of interface.

The contributions of this study include a) understanding the significance of the interface length b) how the presence of elbows and bends effect the axial dispersion and the interface length in any of the given flow regime in the pipelines c) how factors such as pipeline length, pipe diameter, velocity and viscosity effect the length of the interface.

Software will be developed to explain the above studies and also to reduce the axial dispersion in the pipelines which in turn becomes significant in reducing the cost of petroleum.

CHAPTER II

LITERATURE REVIEW

Investigations by Smith and Schulze (1948), Birge (1947), Taylor (1954), Levenspeil (1958), Sjenitzer(1958) and Khizligov (1960) on the spread of contamination or the transmix along the pipeline. Many of them have derived equations taking into consideration, some of the factors such as, length of the pipeline, inner diameter of the pipe, average velocity of the flow in the pipeline, Reynolds number, kinematic viscosity of the mixture, presence of elbows and bends in the pipe, relative roughness and the type of flow regime. Investigators have used some of these factors in obtaining the equations for the interface length. Most of the equations had the interface length as a function of pipe diameter, length of the pipe and Reynolds number.

Birge (1947) derived an empirical relation in which the interface length was directly proportional to a constant power of length. According to Birge (1947) and Smith and Schulze (1948), pipe diameter was not considered as a parameter in calculating the interface length.

Reynolds number was later included in the empirical equation given by Smith and Schulze (1948). Most of the investigators have deduced from the experimental and theoretical studies that the interface length was increasing along the length of the pipeline. So interface length was directly proportional to the power of length and the exponent varied from 0.48 to 0.62. According to Austin and Palfrey (1964), Birge (1947) had exponent on length for the gasoline-gasoline batch to be less than 0.5. This was explained by the fact that Birge (1947) did not take into account the pipe diameter.

$$S = L^{0.62}\left(0.55 + \frac{1075}{\mathrm{Re}^{0.87}}\right) \tag{2.1}$$

(Equation 2.1) given by Smith and Schulze (1948).

Here, S is the interface length, L is the length of the pipe and Re is the Reynolds number.

Smith and Schulze (1948) derived an empirical equation to determine the interface length with a 2 in. pipe which was close to straight but was wound into a large number of coils. According to Taylor (1954), Smith and Schulze's (1948) equation overestimated the interface length in some cases and under-estimated the interface length in other. This was due to the use of a short pipe and also the presence of pumps on both the sides, which had a greater dispersion effect on the flow. Austin and Palfrey (1964) deduced that when a pipe was wound into a large number of coils the transition of Reynolds number from laminar to turbulent regime depends on the ratio of radius of curvature of the coil to the radius of the pipe. As, this ratio decreases, Reynolds number increases, which in turn decreases the interface length in the turbulent region. Taylor (1954), by his experimental studies showed that the presence of elbows and bends also increase the axial dispersion coefficient and bends also results in more friction in both laminar and turbulent flow regimes. So, Taylor (1954) deduced that the interface length increases when the flow stays in the laminar regime or when the friction factor increases in the bends and elbows.

Austin and Palfrey Model:

Most investigators have deduced that the interface length is directly proportional to the pipe length and Reynolds number. But Austin and Palfrey (1964), with their experimental works deduced that interface length was different for the laminar and the turbulent regime. They also explained that the interface length was different in turbulent region when it was above and below the critical region. From (Figure 2.1) they explained that at the lower Reynolds region in the turbulent regime, the axial dispersion coefficient decreases rapidly as the Reynolds number increases. But in the higher Reynolds region in the turbulent regime, axial dispersion coefficient does not show a considerable change with the increase in Reynolds number. Birge (1947) and Weyer (1962) explained earlier that this was due to the difference in viscosities and densities of the two fluids, but they did not have enough evidence to support this hypothesis.

Austin and Palfrey (1964) derived two equations, observing the phenomena in the turbulent regime. They also pointed out that the transition region in the turbulent regime occurs at higher Reynolds number as the diameter increases.

If Reynolds number is above the critical value in the turbulent region, then (Equation 2.2)

$$\text{For} \quad \mathrm{Re} > 10000 \exp\left(1.52\sqrt{d}\right) \qquad (2.2)$$

$$S = 11.75\,\mathrm{Re}^{-0.1}\sqrt{dL} \tag{2.3}$$

When Reynolds number is below the critical value in the turbulent regime, then (Equation 2.5).

$$\text{For } \mathrm{Re} \le 10000\exp\left(1.52\sqrt{d}\right) \tag{2.4}$$

$$S = 18420\,\mathrm{Re}^{-0.9}\sqrt{dL}\exp\left(1.21\sqrt{d}\right) \tag{2.5}$$

Where Re is the Reynolds number, d is the inner diameter of the pipe, S is the length of the interface and L is the length of the pipe.

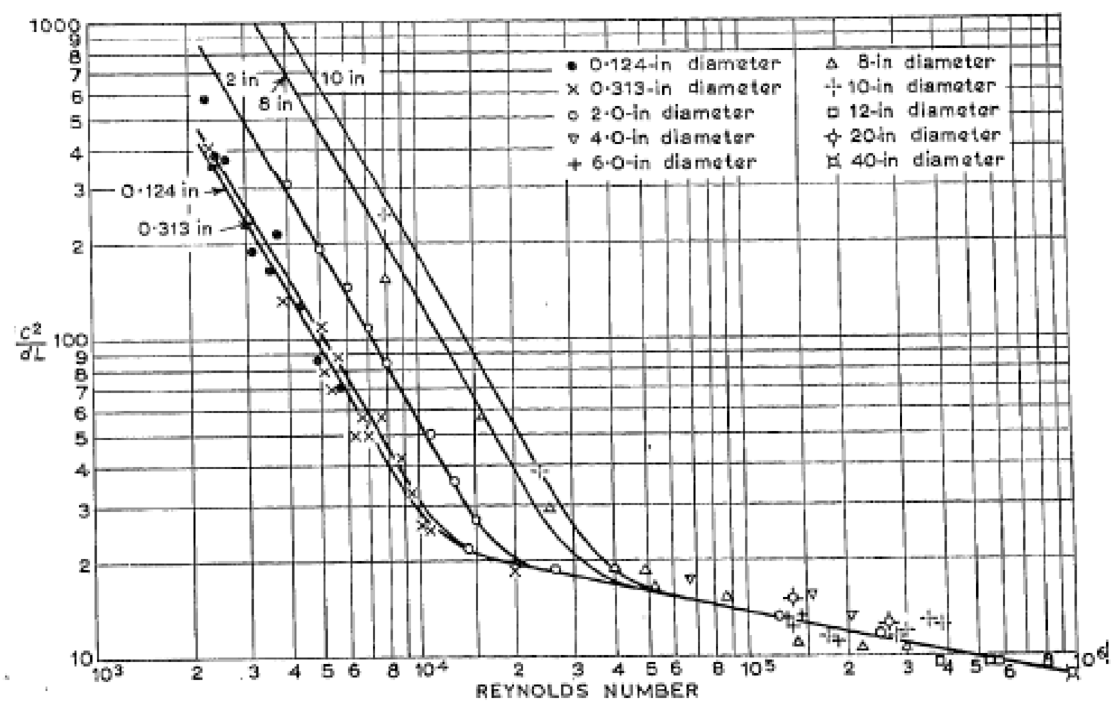


Fig. 2.1 Relationship between Longitudinal dispersion factor and Reynolds Number. From Austin and Palfrey (1964)

From (Figure 2.1) it has been noticed that the turbulent regime has been divided above and below the critical Reynolds number. But at a certain Reynolds number, one of the curve disappears. Austin and Palfrey (1964) gave an assumption that it might be due to the presence of the boundary layer thickness. Taylor (1954) has already stated that the axial dispersion plays an important role in the increase of the interface length. Udeotek and Nguyen (2009) proposed a theory on the disappearance of the curve in the above critical region, stating that the central turbulent flow formed in the turbulent regime stops the fluid from mixing, which may lead to decrease in the axial dispersion coefficient. Austin and Palfrey (1964) have deduced that the critical Reynolds number is different for pipes of different diameters.

Patrachari (2012) has done investigations on the effect of boundary layer thickness and the axial dispersion on the interface length. Researchers have noticed that when the fluid flows in a pipeline, a laminar sub layer forms near the wall of the pipeline, which enhances the mixing, leading to an increase in interface length. Viscous sub layer is an important factor in enhancing of mixing or increase of the interface length, but researchers have not found the extent in which it effects the interface length. Patrachari (2012) derived the model equations in which viscous sub layer thickness was included as one of the factors.

The higher mixing rates in the lower Reynolds region of the turbulent regime has been explained by the presence of viscous boundary layer. According to Patrachari (2012) the central turbulent core that is formed near the boundary layer has been a contributing factor to the axial dispersion. From the mathematical model it was derived that shear stress that is exerted on the fluid is a result of the pressure drop and the axial dispersion. So the equations that are valid for pressure drop can be used in the axial dispersion approximations with some modifications.

$$\frac{K_E}{D} = \left(1 - \frac{\delta}{R}\right)\left(\frac{R^2 u_{\delta,corr}^2}{192D}\right)\frac{1}{\bar{U}\,d} + \left[1 - \left(1 - \frac{\delta}{D}\right)^2\right]\left(3.57\sqrt{f}\right) \qquad (2.6)$$

K_E is the steady state effective dispersion of the straight pipe, δ is the thickness of the viscous region is the radius of the pipe, D is the molecular diffusion coefficient, $u_{\delta,corr}^2$ is corrected velocity. At the viscous region, $\bar{U}$ is the average flow velocity, f is the friction factor, d is the diameter of the pipe.

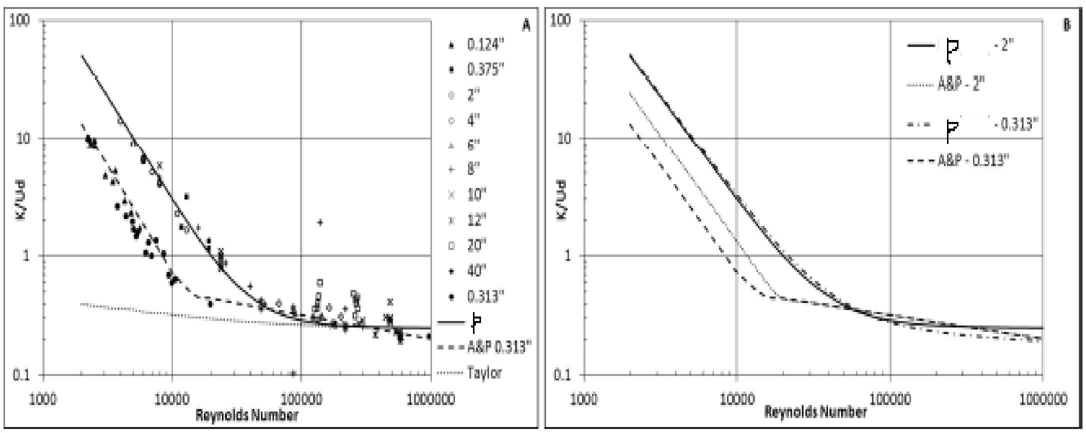


Fig 2.2 Reynolds number vs axial dispersion coefficient Austin & Palfrey (1964) and Patrachari (2012). From Patrachari (2012)

From the (Figure 2.2) Patrachari (2012) explained that the curvature near the critical Reynolds region of turbulent regime showed a smooth curve rather than an abrupt change as viscous boundary layer was taken into consideration and a sharp curve by Austin and Palfrey (1964) equation as they used two different equations for the regions in the turbulent regime. It was inferred from the experiments by Patrachari (2012) that the pipes with diameters 0.123” and 0.313” overestimates the contamination length, due to the fact that these were shorter pipes where equilibrium was not achieved by the convective and diffusive transport mechanisms. So, the model equation proposed by Patrachari (2012) was not applicable for pipes with diameter less than 0.3”. Further studies need to be done on how the interface length is effected by the differences in density and viscosity, pipe roughness.

In summary factors that influence the Transmix Length:

1) Inner diameter of the pipe
2) Average velocity of flow in the pipeline
3) Distance travelled by the transmix.
4) Kinematic viscosity of the fluids.
5) Friction coefficient of the pipe.
6) Relative roughness of the pipe
7) Presence of bends and elbows in the pipe.
8) Strength of turbulence.

Viscosity of mixture:

Viscosity of the fluid plays an important role in the growth of the interface length across the pipe. Viscosity plays a vital role in the molecular diffusion between the layers of flow by momentum. Diffusion of the molecules is directly proportional to the movement of the molecules and inversely proportional to the viscosity. As the viscosity gets higher, diffusion is reduced.

According to Birge (1947), when gasoline-gasoline and diesel-diesel products were sent through a pipeline, the diesel-diesel had lesser transmix when compared to the gasoline-gasoline mix, even though the relative viscosities of the two gasoline and the two diesel batches were the same. The interface length was greater in the gasoline-gasoline mix as the absolute viscosity was greater for gasoline. Birge (1947) also stated that the difference in density between the products is also a factor on the interface length. A fluid with greater density has more gravitational force which influences the spread of contamination. When two fluids of different densities are sent in a pipeline, the higher density fluid overruns the lower density fluid which increases the amount of transmix. But after a while, the interface has almost the same density as the higher density liquid, so the contamination rate decreases.

So, it's important to calculate the viscosity mixture of the two fluids to know the interface length. The Viscosity of mixture can be estimated using the Refutas equation. The Refutas equation uses kinematic viscosity in (cSt) and mass fraction of the fluids that are sent in the pipeline. The kinematic viscosity of each fluid is attained at the same temperature.

$$VBN = 14.534 \ln\left[\ln\left(\upsilon + 0.8\right)\right] + 10.975 \tag{2.7}$$

Where VBN is the Viscosity blending number of each component in the mixture flowing in the pipeline.

$$VBN_{Blend} = \left(x_A * VBN_A\right) + \left(x_B * VBN_B\right) \tag{2.8}$$

VBN_A is the viscosity blending number of component A.

VBN_B is the viscosity blending number of component B.

x_A and x_B are the mass fractions of component A and B respectively.

From (Equation 2.7) and (Equation 2.8) we have, the viscosity of the mixture

$$\upsilon_{Blend} = \exp\left(\exp\left(\frac{VBN_{Blend} - 10.975}{14.534}\right)\right) - 0.8 \qquad (2.9)$$

υ_{Blend} is the viscosity mixture of the two fluids sent in the pipeline.

Inner diameter of the pipe:

Inner diameter of the pipe plays an important role indirectly in the spreading of the interface length. The diameter of pipe has been incorporated with Reynolds number in most of the equations. Many of the investigators such as Jablonski (1946), Taylor (1954) and Sjentitzer (1958) have given empirical equations which have the interface length proportional to the diameter of the pipe. According to Austin and Palfrey (1964) the interface length is directly proportional to the square root of the diameter of the pipe. Austin and Palfrey (1964) have given two equations for the interface length depending on the critical Reynolds number. From the equations given by Austin and Palfrey (1964) it has been deduced that the interface length is higher at lower Reynolds number than the higher Reynolds number when the diameter is kept constant.

Reynolds number:

Investigators have determined that the interface length is a function of the Reynolds number. From the empirical formulas of most of the investigators such as Jablonski (1946), Taylor (1954) and Sjentitzer (1958), it can be incurred that the Reynolds number is inversely proportional to the interface length. According to Austin and Palfrey (1964) and Patrachari (2012), the effect of Reynolds number is different for the laminar and turbulent regions. The turbulent region showed less interface length compared to the laminar region. The region below the above Reynolds number showed a greater interface length when compared to the one below the critical Reynolds number.

$$\mathrm{Re} = \frac{\rho V d}{\mu} = \frac{V d}{\upsilon} \qquad (2.10)$$

Where Re is the Reynolds number, ρ is the density of the fluid, V is the average velocity of the fluid, d is the inner diameter of the pipe, μ is the dynamic viscosity and υ is the kinematic viscosity of the mixture. υ can be calculated using (Equation 2.9).

Length of the pipe:

The interface length in a pipe is dependent on the length of the pipeline. According to the investigators such as Jablonski (1946), Taylor (1954) and Austin &Palfrey (1964) the interface length is directly proportional to the square root of the pipe length. Interface length increases as the fluids travels down the pipe length. So longer pipes have more transmix than the shorter pipes. Pipelines also consists of bends and elbows. The presence of the bends and elbows increases the equivalent length of the pipe and also increases the mixing of the fluid. Mixing in turn increases the transmix.

Friction factor:

One of the factors which influence the interface length is Friction factor. Relative roughness is expressed as $\frac{\varepsilon}{D}$, where ε is the roughness of the pipe and d is the inner diameter. According to Taylor (1954), pipes with high relative roughness show an increase in the interface length. So, pipes with small diameter show an increasing interface length compared to large diameter pipes. Taylor (1954) also deduced that friction factor increases with the presence of bends and elbows in the pipeline due to mixing of the fluid. According to the Moody chart when Reynolds number is plotted against the friction factor, the laminar region and turbulent show a definite pattern. As the Reynolds number increases the friction factor decreases. The prediction of friction factor is inconsistent in the transition region and not many investigations are done in this region. Colebrook (1939) has developed an equation to calculate the friction factor. But the equation worked only for the turbulent flows. Many investigators have developed equations basing on the Colebrook equation. Swamee-Jain (1976) gave an approximation to the Colebrook equation which can be applied to circular pipe and the result had less error. Another investigator Serghides (1984) derived an equation which was used for a high range of Relative roughness and Reynolds number.

Friction factor was calculated using the (Equation 2.11) given by Swamee-Jain (1976).

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7d} + \frac{5.74}{\mathrm{Re}^{0.9}}\right) \tag{2.11}$$

ε is the absolute roughness of the pipe, d is the inner diameter of the pipe , f is the friction factor and Re is the Reynolds number.

CHAPTER III

EQUATIONS FOR INTERFACE LENGTH

Pipelines are used in transporting the fluids from the gathering systems to the point where it has to be delivered. So almost the same pipelines are used in transporting the fluids of different qualities and characteristics in a series. When the fluids are sent in series, mixing occurs at the interface diminishing the quality of the liquid with high grade. Following equations are used to calculate the volume of transmix.

When two fluids having different viscosities are sent in series forming an interface, the viscosity of the transmix must be determined. The Viscosity of mixture can be estimated using the Refutas equation. The Refutas equation uses kinematic viscosity in (cSt) and mass fraction of the fluids that are sent in the pipeline. The kinematic viscosity of each fluid is attained at the same temperature.

$$VBN = 14.534 \ln\left[\ln\left(\upsilon + 0.8\right)\right] + 10.975 \tag{3.1}$$

Where VBN is the Viscosity blending number of each component in the mixture flowing in the pipeline.

$$VBN_{Blend} = \left(x_A * VBN_A\right) + \left(x_B * VBN_B\right) \tag{3.2}$$

VBN_A is the viscosity blending number of component A.

VBN_B is the viscosity blending number of component B.

x_A and x_B are the mass fractions of component A and B respectively.

From (Equation 2.7) and (Equation 2.8) we have, the viscosity of the mixture as:

$$\upsilon_{Blend} = \exp\left(\exp\left(\frac{VBN_{Blend} - 10.975}{14.534} \right) \right) - 0.8 \qquad (3.3)$$

υ_{Blend} is the viscosity mixture of the two fluids sent in the pipeline.

Reynolds number:

Reynolds number of a fluid flowing in the pipeline is given by (Equation 3.4).

$$\mathrm{Re} = \frac{\rho V d}{\mu} = \frac{Vd}{\upsilon} \qquad (3.4)$$

Where Re is the Reynolds number, ρ is the density of the fluid, V is the average velocity of the fluid, d is the inner diameter of the pipe, μ is the dynamic viscosity and υ is the kinematic viscosity of the mixture. υ can be calculated using (Equation 3.3).

Average Velocity:

Average velocity of the fluid flowing in the pipeline is calculated using (Equation 3.5).

$$V = \frac{Q}{A} = \frac{4Q}{\pi d^2} \tag{3.5}$$

V is the average velocity of the fluid flowing in the pipeline, Q is the volumetric flow rate, A is the cross-sectional area of the pipe and d is the inner diameter of the pipe.

Equivalent Length:

Pipelines consist of bends and elbows which are used to change the direction of flow of the fluid in a pipeline. Volume of transmix increases due to bends and elbows as the mixing enhances. So, it is important to calculate the equivalent length of pipeline. It is given by (Equation 3.6).

$$l_e = \frac{K_L d}{f} \tag{3.6}$$

l_e is the equivalent length of the pipe, d is the inner diameter of the pipe and f is the friction factor. K_L is calculated using (Equation 3.7).

$$K_L = K_{L,elbows}(e) + K_{L,tees}(t) + K_{L,union}(u) + K_{L,valves}(v) \tag{3.7}$$

K_L is the loss coefficient.

$K_{L,elbow}$ is the loss coefficient of the elbows

$K_{L,tees}$ is the loss coefficient of the tees.

$K_{L,union}$ is the loss coefficient of the union Threaded .

$K_{L,valves}$ is the loss coefficient of the valves.

e is the number of elbows , t is the number of tees,u is number of union threaded and v is the number of valves in the pipe.

Friction factor:

Colebrook (1939) has developed an equation to calculate the friction factor. But the equation worked only for the turbulent flows. Swamee-Jain (1976) gave an approximation to the Colebrook equation which can be applied to circular pipe and the result had less error.

Friction factor was calculated using (Equation 3.8) given by Swamee-Jain (1976).

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7d} + \frac{5.74}{\mathrm{Re}^{0.9}}\right) \qquad (3.8)$$

ε is the absolute roughness of the pipe, d is the inner diameter of the pipe ,f is the friction factor ,Re is the Reynolds number.

Interface Length:

For the software development of the present study Austin and Palfrey (1964) equation was used in calculating the interface length. (Equation 3.9) represents the critical Reynolds number .If the Reynolds number is above the critical (Equation 3.10) and if Reynolds number is below the critical (Equation 3.12) were used respectively.

$$\text{For } \mathrm{Re} > 10000\exp\left(1.52\sqrt{d}\right) \qquad (3.9)$$

$$S = 11.75\,\mathrm{Re}^{-0.1}\sqrt{dL} \qquad (3.10)$$

For $\mathrm{Re} \leq 10000 \exp\left(1.52\sqrt{d}\right)$ (3.11)

$$S = 18420 \mathrm{Re}^{-0.9} \sqrt{dL} \exp\left(1.21\sqrt{d}\right) \quad (3.12)$$

Re is the Reynolds number, S is the interface length, d is the inner diameter of the pipe and L is the length of the pipeline.

Volume of Transmix:

Volume of the transmix is calculated using Equation (3.13)

$$V_{Interface} = \frac{\pi d^2}{4} S \quad (3.13)$$

$V_{Interface}$ is the volume of the interface, d is the inner diameter of the pipe and S is the interface length.

CHAPTER IV

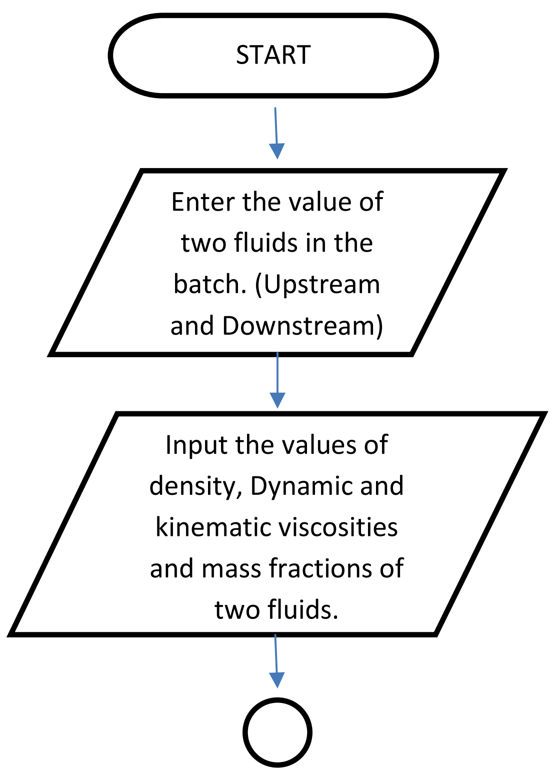
SOFTWARE DEVELOPMENT

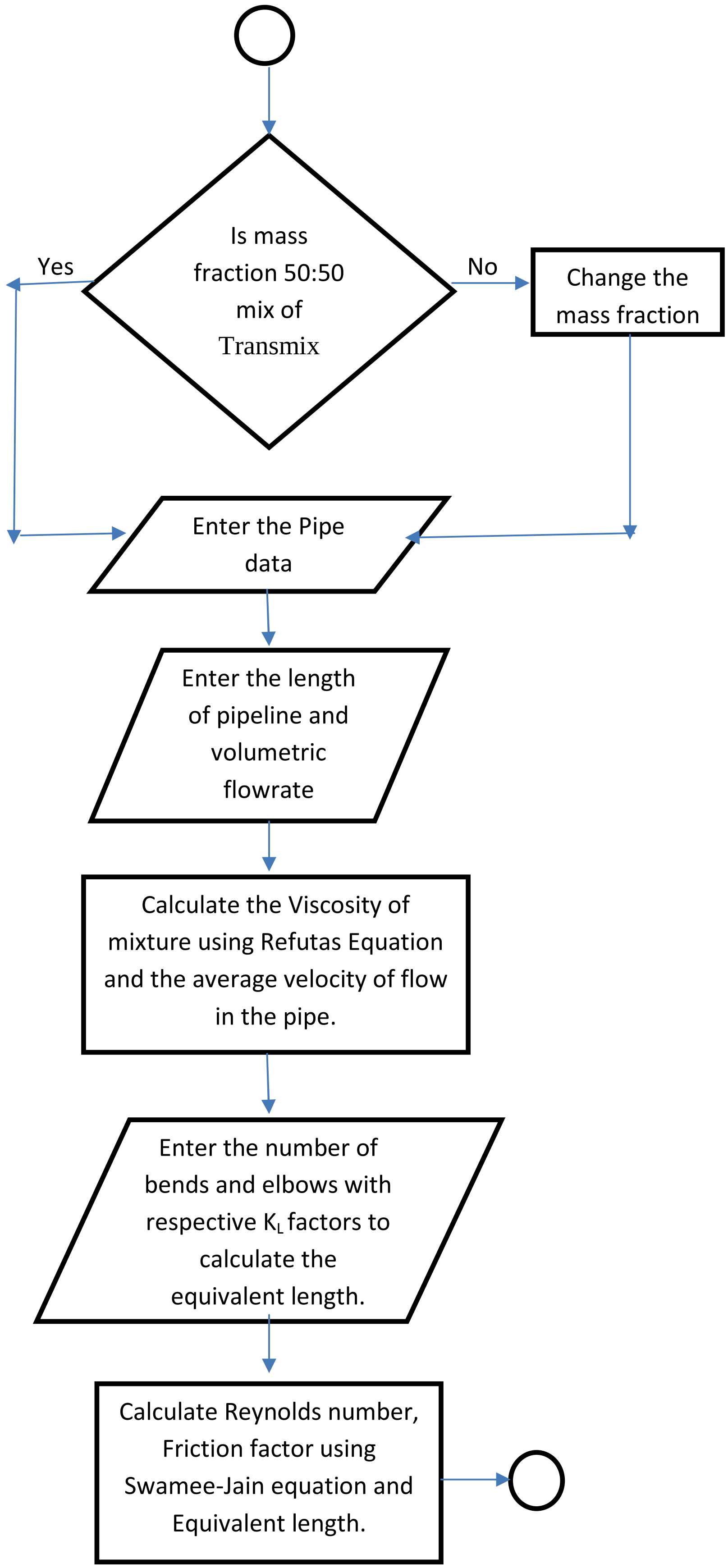
The software developed in this study calculates the length and volume of the interface of two fluids sent as a batch along the length of a pipeline. In the present study, Masse and Johannes (2002) program was improved, errors were corrected and was made more user friendly. The Masse and Johannes (2002) program calculated the interface length using the equation developed by Smith and Schulze (1948). In the present study, equations developed by Austin and Palfrey (1964) were used to calculate the interface length as it has the diameter included in the equation ,which is also a secondary parameter effecting the increase or decrease of the interface length.

A maximizing and minimizing button was included in the program as it was a tough task for the user to access the excel sheet when the program was running, using Masse and Johannes (2002) software. The present study also facilitates the ability to change the mass fraction of the fluids, apart from its default value of 50:50 mix. The main drawback of Masse and Johannes (2002) software was, having too many Userforms, which may confuse the user in the beginning. The presence of bends and elbows play a significant role in the increase of transmix volume, which was not included in the software by Masse and Johannes (2002). The present software has a provision to calculate the equivalent length added from the elbows, valves and tees.

A graph of interface volume along the length of the pipeline in Masse and Johannes (2002) code gave a straight line and an increase in the length of the interface along the length of the pipeline with a slope nearly equal to 0.5, but did not show the transmix volume of the particular length entered by the user. In this study a mark with red dot had been created to show the volume of the interface for the user entered value. So, Userforms were improved, made error free and user-friendly.

Flowchart:




Is mass fraction 50:50 mix of Transmix
Yes
No
Change the mass fraction
Enter the Pipe data
Enter the length of pipeline and volumetric flowrate
Calculate the Viscosity of mixture using Refutas Equation and the average velocity of flow in the pipe.
Enter the number of bends and elbows with respective K_L factors to calculate the equivalent length.
Calculate Reynolds number, Friction factor using Swamee-Jain equation and Equivalent length.

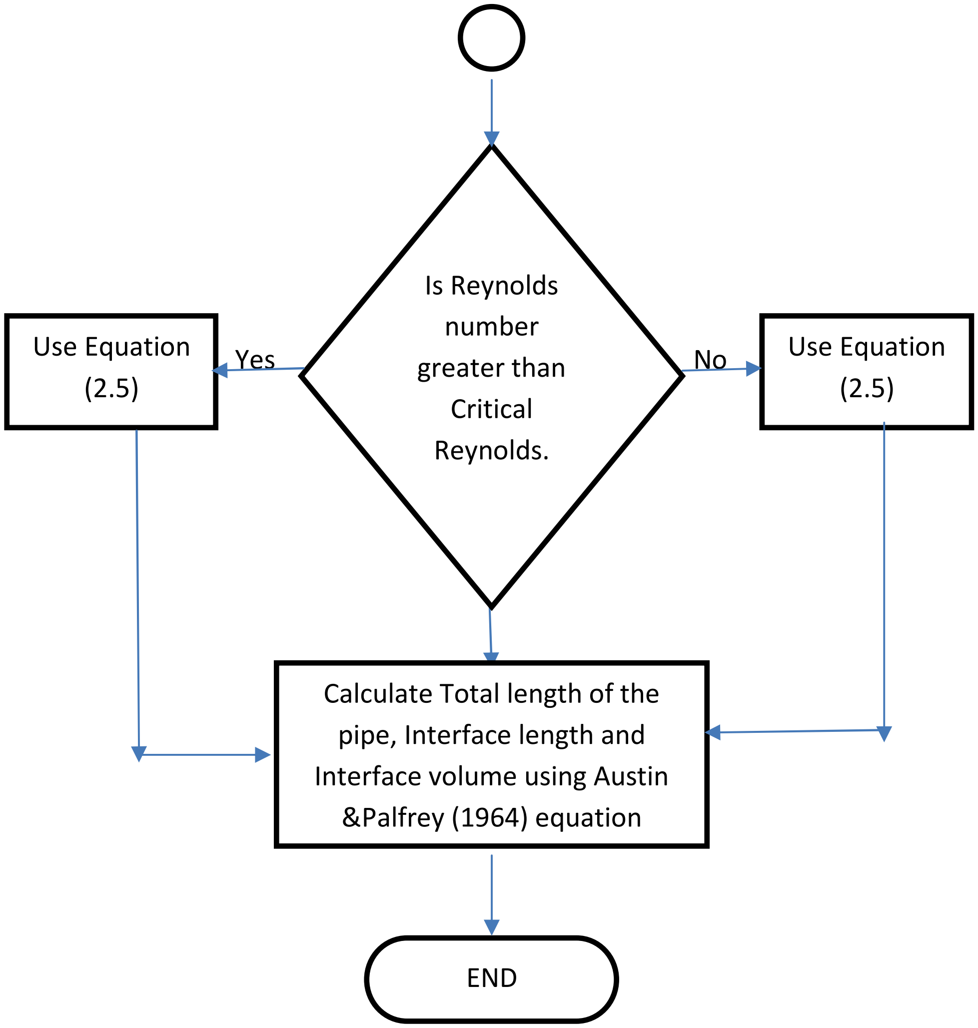


Fig 4.1 Flowchart

Fluid Properties UserForm:

1) The main UserForm was divided with tabs including Introduction, Fluid Properties, Pipe data, Pipe line data, Equivalent length and Calculations.
2) Figure 4.2 shows the Fluid properties tab which has the provision to add the upstream and the downstream fluids from the database. The database is set up in the "Fluid Properties" tab of the worksheet. Downstream is the leading liquid and upstream is trailing liquid.

3) As the user selects the upstream or the downstream fluid from the combo box, it automatically adds the density (lb. /bbl.), dynamic viscosity (cP) and kinematic viscosity (cSt) of that fluid with respective units in the textboxes. The conversions that are used in the petroleum industry for density, dynamic and kinematic viscosity have been added.

4) Mass fractions of the fluids are by default taken as 50:50 mix of the interface. The user can manually input the mass fractions by using the command button "change mass fraction".

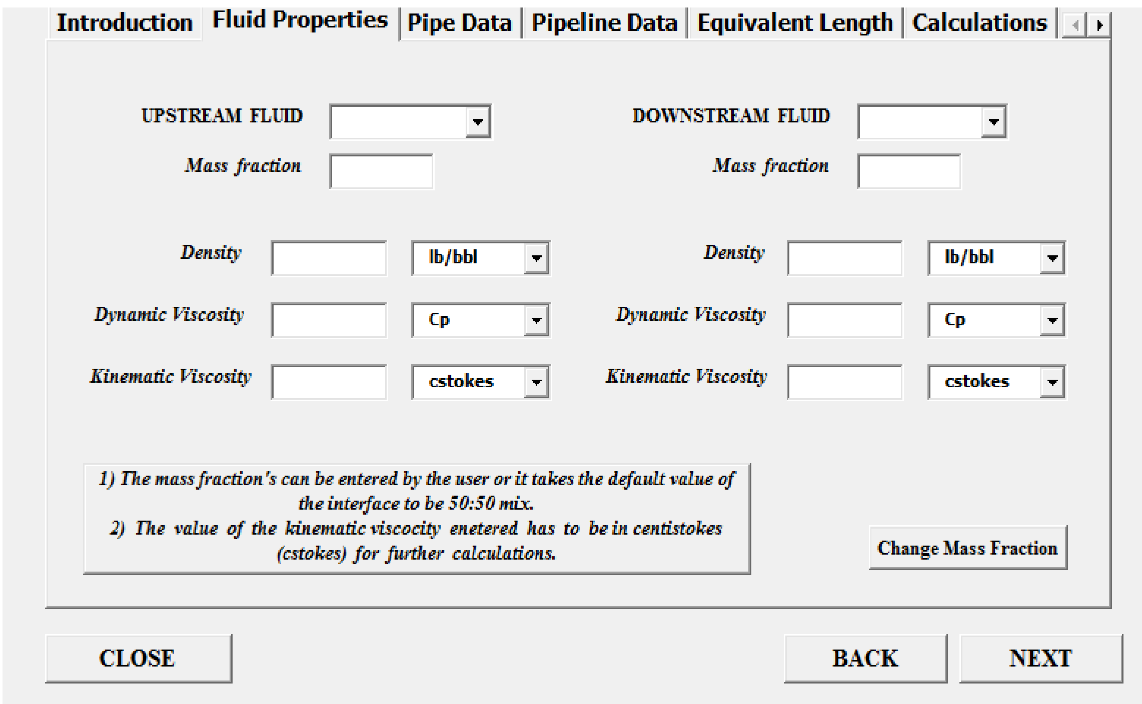


Fig. 4.2 Fluid Properties

5) The kinematic viscosity entered has to be in cSt (centistokes) as the equation used in calculating the kinematic mixture requires the kinematic viscosity in cSt.

6) The properties of the upstream and downstream fluid on the UserForm are directly input to the “Fluid Data” tab of the worksheet.
7) Next command button is used in forward navigation of the page.
8) Back command button is used for backward navigation.
9) Close command button unloads the Userform.

Pipe Data Userform:

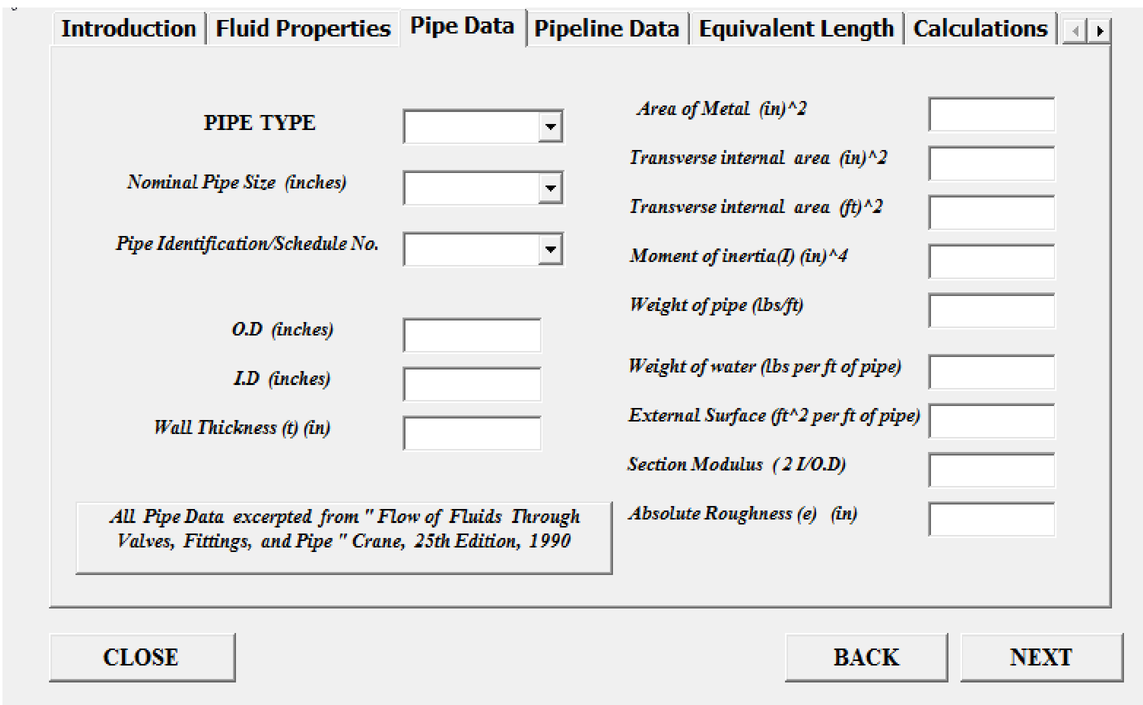


Fig. 4.3 Pipe Data excerpted from the “Flow of fluids through valves, fittings and pipes by Crane (1990)

Figure 4.3 represents the pipe data excerpted from Cranes book. Database of “Steel, Stainless Steel and Iron pipe” have been included. The nominal pipe sizes range from 1/8“ to 36 " Steel, Stainless Steel and Iron pipes have their respective pipe identification or the Schedule numbers. Iron pipe is identified by STD, XS or XXS; Steel pipe by 20, 30, 40, 60, 80, 100, 120, 140 and 160; Stainless steel by 5S, 10S, 40S and 80S. The database of the pipe properties have been set up in the "pipe data table" tab of the worksheet. Absolute roughness factors of different pipe types have also been added. The Pipe data from the UserForm is input to the "Pipe Properties" tab of the worksheet.

Pipeline Data Userform:

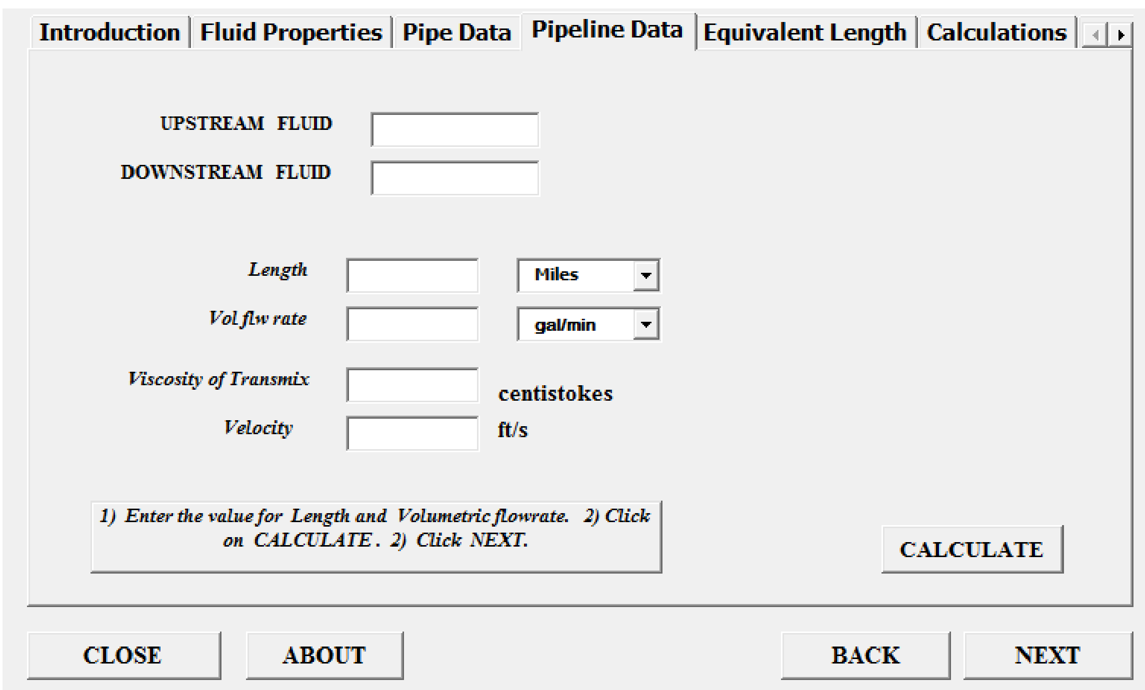


Fig. 4.4 Pipeline Data

1) Figure 4.4 allows input of pipeline data. Textboxes of upstream and downstream fluid shows the fluids selected by the user in the Fluid Properties Tab.

2) Length and volumetric flow rates required inputs by the user. Conversions for length and volumetric flow rates are available in the software. Viscosity of the transmix and the average velocity of the fluid flowing in the pipeline are calculated.

3) Viscosity of the transmix or the mixture can be calculated using (Equation 3.3). Viscosity of the mixture can be estimated using the Refutas equation. Refutas equation uses the kinematic viscosity in (cSt) and mass fraction of the fluids sent in the pipeline. The kinematic viscosity of each fluid is attained at the same temperature.

4) Average velocity of the fluid flowing in the pipeline is calculated using Equation 3.5.

Equivalent length Userform:

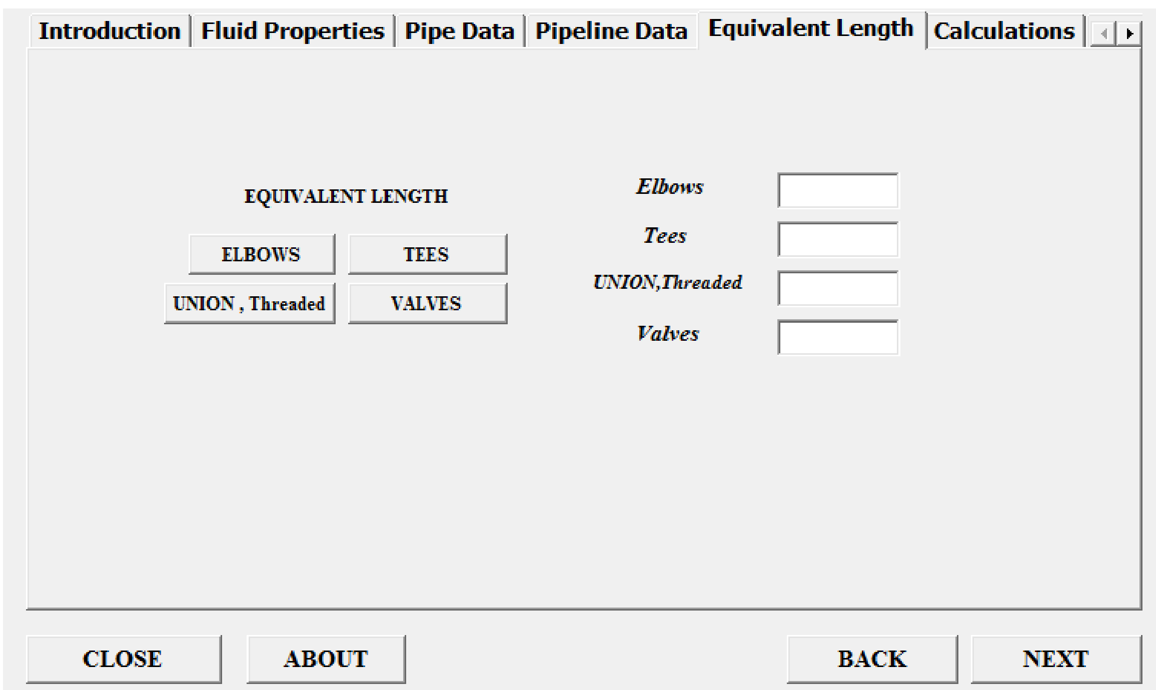


Fig. 4.5 Equivalent Length

Elbows and bends present in the pipe represent the equivalent length of the pipe. Mixing of the fluid increases due to the presence of bends and elbows increasing the length of the interface. Four types of fittings have been added in the database such as Elbows, Tees, Union threaded and Valves. (Figure 4.5) represents the equivalent length in terms of bends and elbows.

Types of Elbows are displayed in (Figure 4.6).The first column of textboxes represent the K_L factors of the fittings and the second column represents the number of elbows of that particular type. User needs to check the boxes to the left of the type of elbows to add it in the calculation of equivalent length.

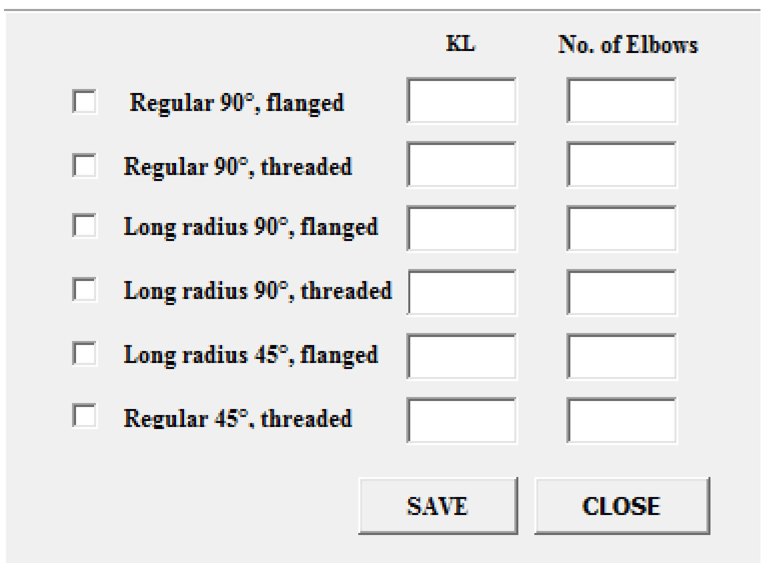


Fig. 4.6 Types of Elbows

Types of Tees are shown in (Figure 4.7). The user can check the box to add a particular type of Tee. If the check box is not selected, textboxes are locked from user entering the data. Save command button on the userform calculates the loss coefficient factors of the fitting. The close command unloads the userform.

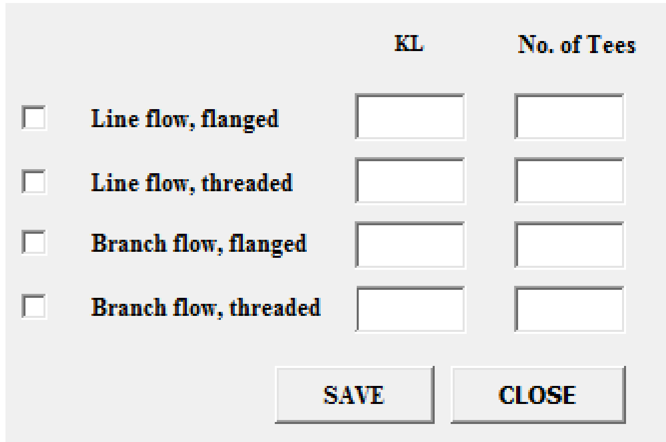


Fig. 4.7 Types of Tees

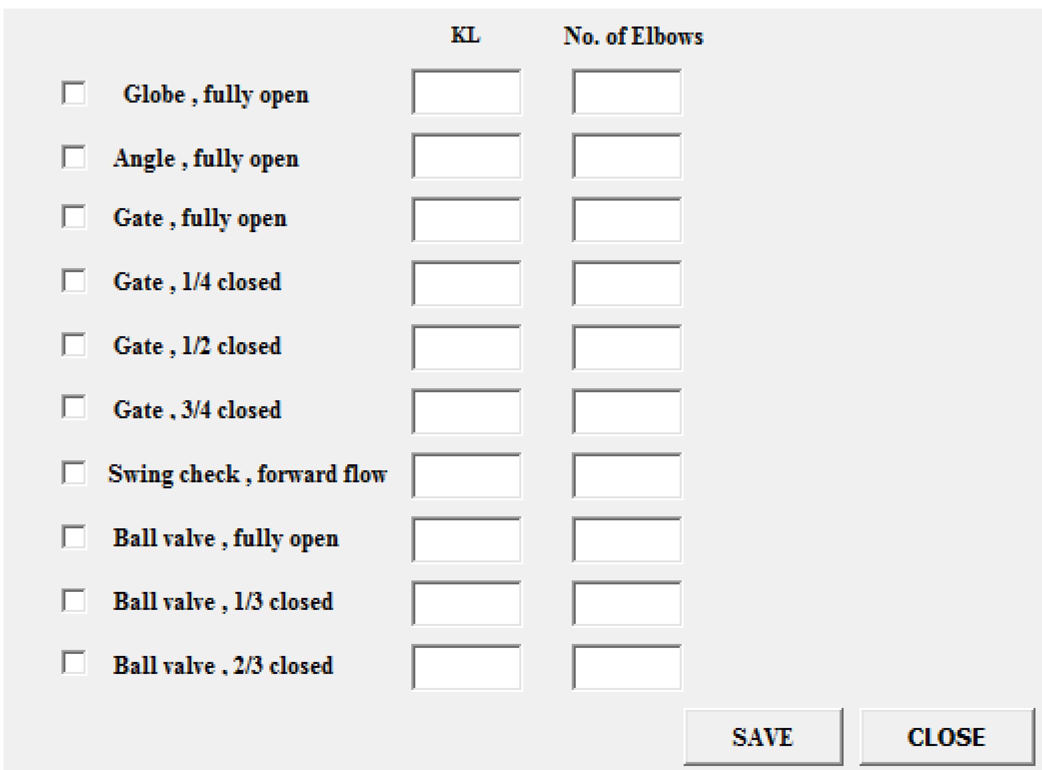


Fig. 4.8 Types of Valves

Types of Valves are shown in (Figure 4.8). The user can check the box to add a particular type of Valve.

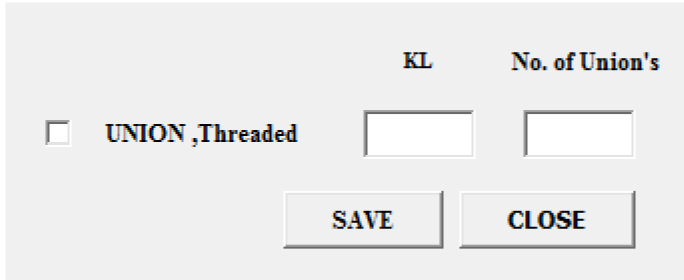


Fig. 4.9 Types of Union Threaded

Types of Union Threaded are shown in (Figure 4.9). The user can check the box to add the Union threaded type. K_L factor was calculated using (Equation 3.7).

Calculations UserForm:

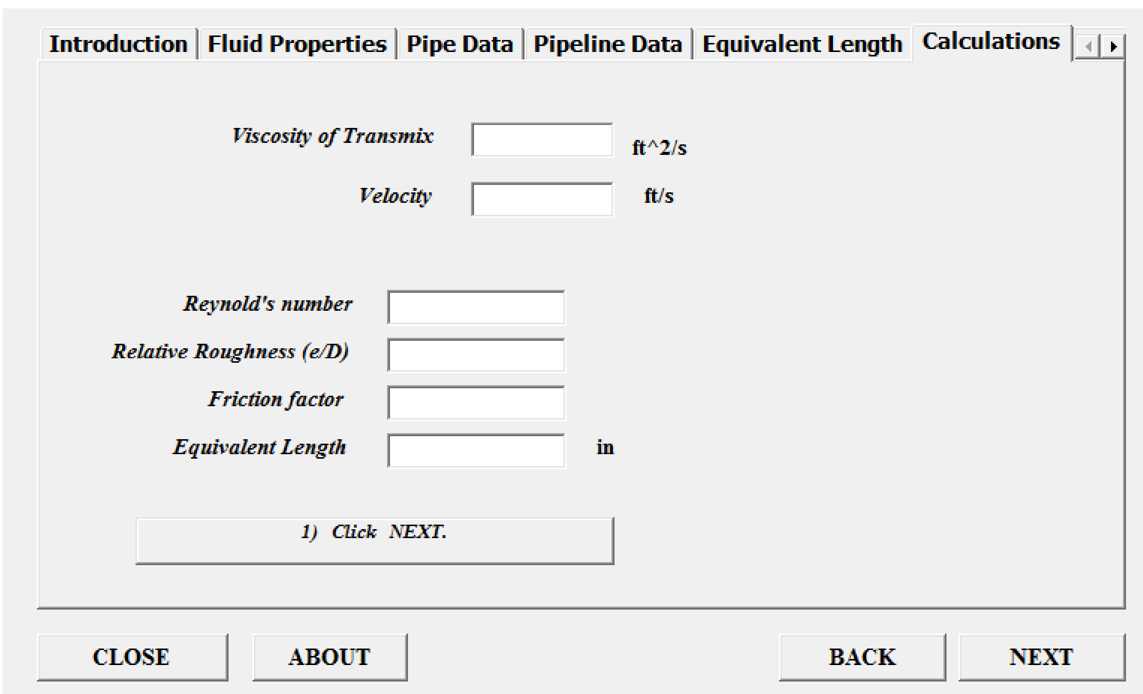


Fig. 4.10 Calculations

Figure 4.10 shows the calculations Userform that summarizes the calculation of Reynolds number, relative roughness factor, friction factor and equivalent length used to estimate the interface length.

1) Viscosity of the transmix or mixture calculated in the Pipeline Data tab has been converted from centistokes to $\frac{ft^2}{s}$ for the calculation of the Reynolds number.

2) Reynolds number of the flow is determined using (Equation 3.4).

3) Friction factor was calculated using the (Equation 3.8) given by Swamee-Jain (1976).

4) Equivalent length of the pipe was calculated using (Equation 3.6).

Transmix UserForm:

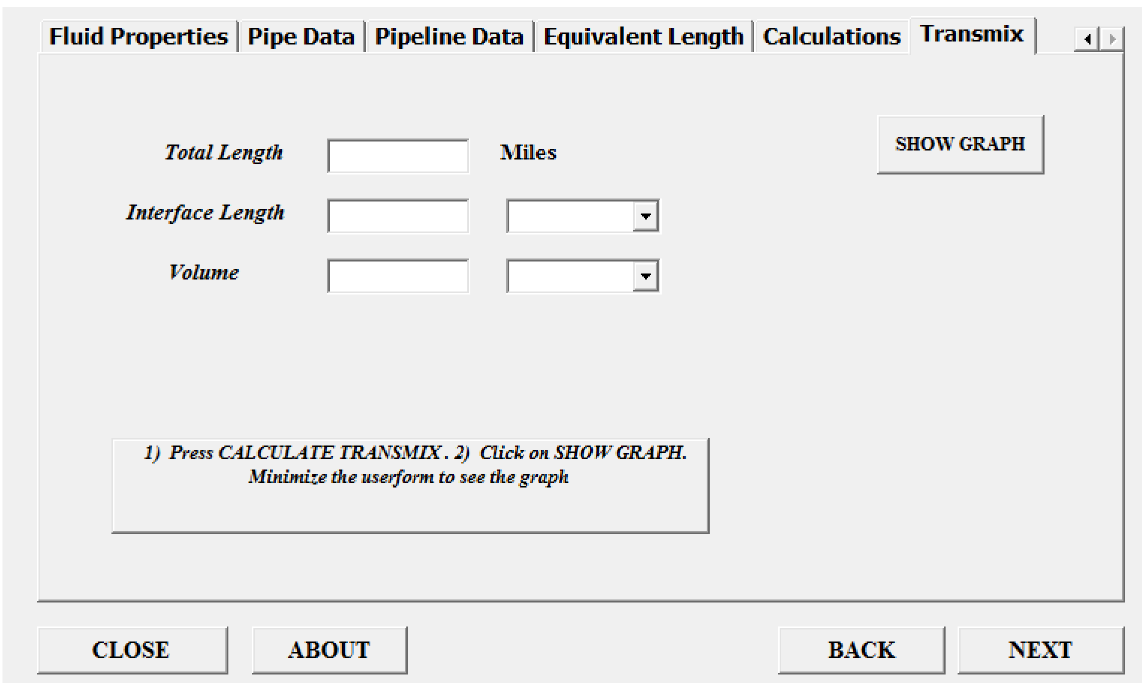


Fig. 4.11 Transmix

Transmix length and volume calculations are shown in (Figure 4.11). Total miles comprises of the length of the pipeline and the equivalent length of the pipeline. The equation given by Austin and Palfrey (1964) was used in calculating the interface length. (Equation 3.9) represents the critical Reynolds number. If the Reynolds number is above the critical (Equation 3.10) and if Reynolds number is below the critical (Equation 3.12) were used respectively. Volume of the transmix was calculated using Equation (3.13)

The Show Graph command button plots the graph of interface volume along the pipe length. “Transmix” tab on the worksheet shows the value of the interface volume for the pipe length ranging from 1 to 1000 miles. “Graph lines” tab on the worksheet are used in setting the horizontal and vertical minor lines on the graph in “Chart1” tab of the worksheet. The blue line on “Chart1” represents the plot of interface volume for the pipe length ranging from 1 to 1000 miles, where in the red point is the interface volume that the user has calculated for a particular length.

Graph Information UserForm:

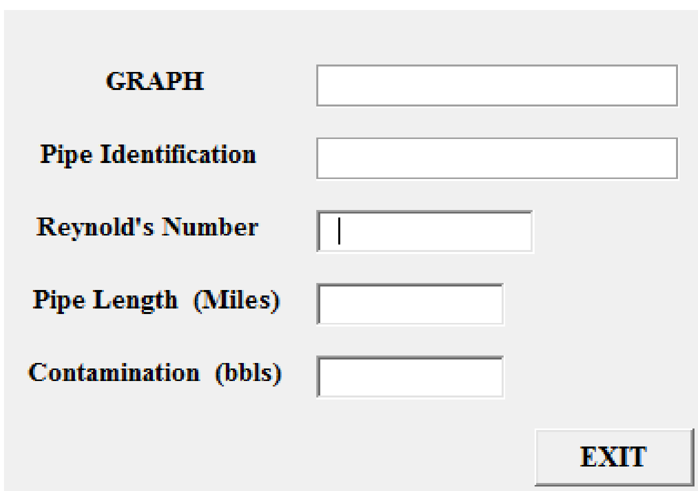


Fig. 4.12 Graph Information

Figure 4.12 shows the graph information available from the “Chart1” tab of the worksheet.

Improvements:

Major improvements of this software were, it was made user friendly, the UserForm was improved and the errors were corrected from the software developed by Masse and Johannes (2002). Some other improvisations include adding the code for the calculation of equivalent length, changes in the graph, mass fractions and adding minimizing and maximizing buttons.

Masse and Johannes (2002) used Smith and Schulze (1948) (Equation 4.1) for the calculation of interface length.

$$S = L^{0.62}\left(0.55 + \frac{1075}{\mathrm{Re}^{0.87}}\right) \tag{4.1}$$

Where S is the interface length, Re is the Reynolds number and L is the length of the pipeline. Smith and Schulze (1948) is independent of inner diameter but Austin and Palfrey (1964) equation deduced that the interface length changes with the diameter.

CHAPTER V

SENSITIVITY ANALYSIS

Based on the investigations done by the researchers, the length of the interface is dependent on the parameters such as pipe length, inner diameter, Reynolds number and average flow velocity of the pipe. The secondary parameters are viscosity, density and mass fraction of the transmix mixture. The present software was developed using the equation given by Austin and Palfrey (1964). Most of the researchers developed equations and experimentally proved that the interface length increases along the length of pipeline. The plot of interface volume with the length of pipe gives a straight line with a slope nearly 0.5 on a semi-log graph.

For $\mathrm{Re} > 10000\exp\left(1.52\sqrt{d}\right)$ (5.1)

$$S = 11.75\,\mathrm{Re}^{-0.1}\sqrt{dL} \tag{5.2}$$

$$\mathrm{Re} \le 10000\exp\left(1.52\sqrt{d}\right) \tag{5.3}$$

$$S = 18420\,\mathrm{Re}^{-0.9}\,\sqrt{dL}\,\exp\left(1.21\sqrt{d}\right) \tag{5.4}$$

Re is the Reynolds number, S is the interface length, d is the inner diameter of the pipe and L is the length of the pipeline. In the present software sensitivity analysis was done on the pipe length, pipe diameter, kinematic viscosity of the fluids, average velocity flow of the pipe and mass fractions of the transmix mixture. Tests were run using different parameters to study the effect on the interface length.

Sensitivity on length of the pipeline:

A pipe with 22” diameter was used as a test case transporting gasoline and kerosene with a volumetric flow rate of 4500 gal/min along a pipeline length ranging from 1 to 10,000 miles.

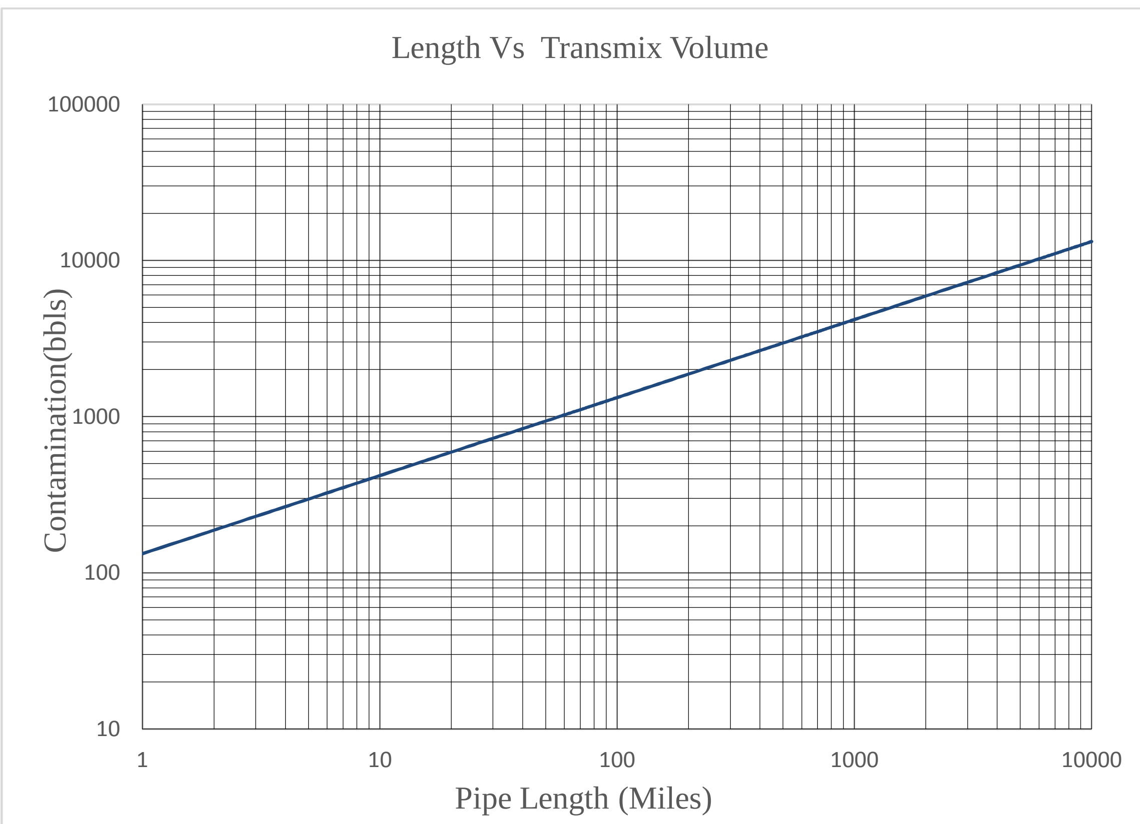


Fig. 5.1 Graph of Length Vs Transmix volume

The graph in (Figure 5.1) is a plot of the volume of transmix along the length of the pipeline. Most of the researchers have predicted that the interface length along the pipe can be stated by the power law, power ranging from 0.48 to 0.62. Austin and Palfrey 1964) has the power of length as 0.5. It can be inferred from (Figure 5.1) that the volume of interface increases with the increase in length of the pipeline. As mixing of fluids increases along the length of the pipeline, axial dispersion increases which results in the increase of the transmix volume.

Sensitivity on average velocity of flow in the pipeline:

A sensitivity test was run to study the effect of average velocity of flow of the fluids on the interface length. A pipe with 20" diameter was used to send gasoline and kerosene along the length of the pipe line ranging from 100 to 400 miles. The test was conducted to determine if the volume of interface changes when the average velocity of flow changes in the pipe at constant diameter. The average velocity of the pipelines in the petroleum industry ranges from 3 to 8 ft /s. The following results were obtained:

Velocity (ft./s)	L= 100	L = 200	L= 300	L=400
	Volume of Interface(bbl.)			
3.30	1066	1507	1846	2132
3.97	1046	1480	1813	2093
4.30	1038	1468	1798	2077
4.63	1030	1457	1785	2061
5.40	1015	1435	1758	2030
5.85	1007	1424	1744	2014
6.51	996	1409	1725	1992
6.95	989	1399	1714	1979
7.28	985	1393	1706	1970

Table 5.1 Volume of interface with velocity

From (Figure 5.2) it can be inferred that the volume of interface is decreasing as the average velocity of fluid is increasing when the diameter of the pipe is kept constant. The boundary layer thickness of the fluid increases which ensues the decrease in velocity of the fluid. So, the downstream fluid at the center of the pipe moves with a different velocity leaving the fluid at the boundary or walls travelling at a lower velocity. This trailing liquid in turn mixes with the upstream fluid resulting in more contamination of the fluid. So a pipe with average velocity of flow (5 to 7) ft /s would be recommended to reduce the volume of transmix.

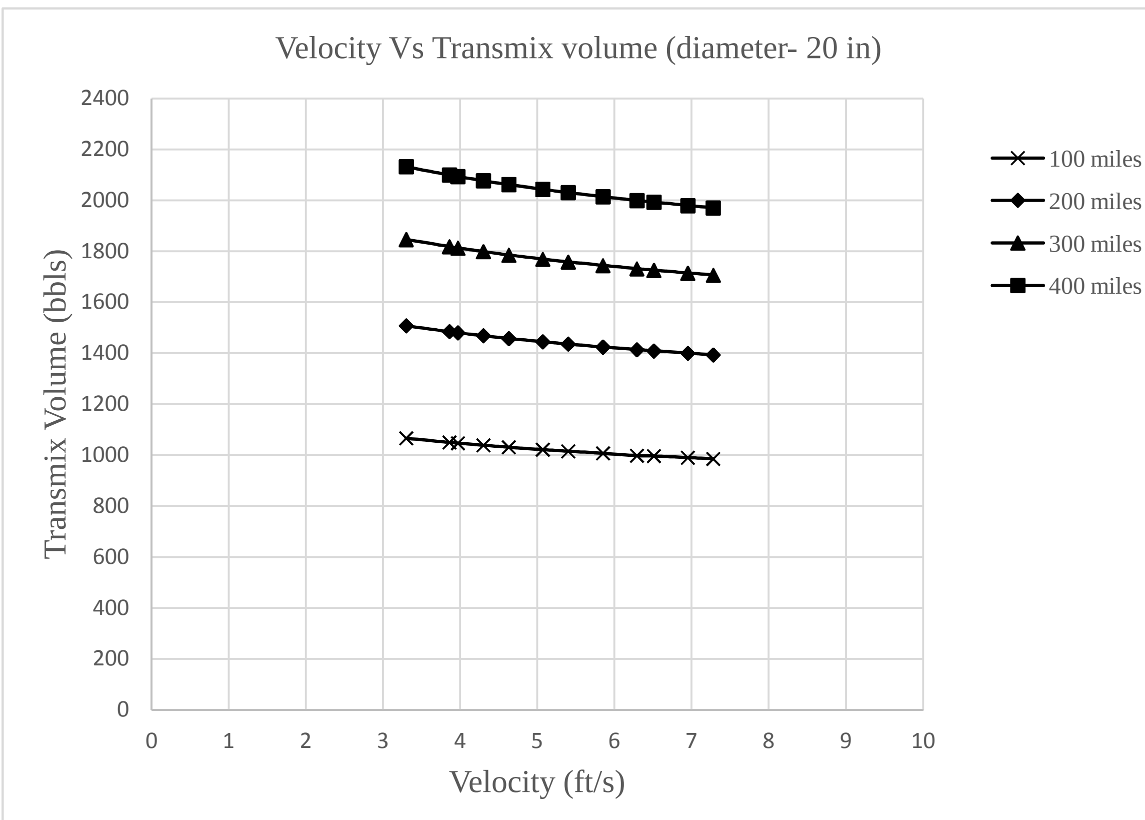


Fig. 5.2 Graph of Velocity vs Transmix volume

Mass fractions of the Transmix mixture (Similar Viscosities):

A sensitivity test has been done on the fluids in upstream and downstream, changing the mass fractions. The leading fluid is known as the downstream fluid and trailing is called the upstream fluid. Software developed in this study allows the user to enter the mass fractions or it takes the default value to be a 50:50 mix. A pipe with 18" diameter was used in transporting diesel and kerosene at a velocity of 4.4 ft /s. Diesel and Kerosene have kinematic viscosities of 2.6 and 2.71 centistokes respectively. Kerosene is a high viscous fluid among the two fluids.

Upstream Fluid	Downstream Fluid	Transmix volume(bbls)
Diesel	Kerosene	
0.1	0.9	1224.3
0.5	0.5	1221.1
0.9	0.1	1220.2

Table 5.2 Sensitivity with mass fractions (Similar Viscosities 1)

Upstream Fluid	Downstream Fluid	Transmix volume(bbls)
Kerosene	Diesel	
0.1	0.9	1220.2
0.5	0.5	1221.1
0.9	0.1	1224.3

Table 5.3 Sensitivity with mass fractions (Similar Viscosities 2)

From (Table 5.2) and (Table 5.3) it can be inferred that the transmix volume remains about the same if the transmix is a 50:50 mix, even if the upstream and the downstream fluids are interchanged. When a fluid with high viscosity is selected as the downstream fluid, it travels slowly resulting in mixing with the upstream fluid, which slightly increases the volume of transmix. So, the mass fractions have only a minor effect on the calculation of the transmix amount if the viscosities are almost similar.

Mass fractions of the Transmix mixture (Difference in Viscosities):

In this test gasoline and kerosene are sent as a batch as the fluids have difference in viscosities. A pipe with 20” diameter was used in transporting gasoline and kerosene at a velocity of 4.5 ft/s. Gasoline and kerosene have kinematic viscosities of 0.64 and 2.71 centistokes respectively. Kerosene is a high viscous fluid among the two fluids.

Upstream Fluid	Downstream Fluid	Transmix Volume (bbls)
Gasoline	Kerosene	
0.1	0.9	1099
0.5	0.5	1030
0.9	0.1	980

Table 5.4 Sensitivity of mass fractions (Difference in Viscosities 1)

Upstream Fluid	Downstream Fluid	Transmix Volume (bbls)
Kerosene	Gasoline	
0.1	0.9	980
0.5	0.5	1030
0.9	0.1	1099

Table 5.5 Sensitivity of mass fractions (Difference in Viscosities 2)

From (Table 5.4) and (Table 5.5) it can be inferred that the transmix volume remains about the same if the transmix is a 50:50 mix, even if the upstream and the downstream fluids are interchanged with fluids having similar or difference in viscosities. When a fluid with high viscosity is selected as the downstream fluid with high mass fraction, it travels slowly resulting in mixing with the upstream fluid, which significantly increases the volume of transmix. So, the mass fractions have a major effect on the calculation of the transmix amount if there is difference in viscosities.

Sensitivity on Viscosity of the fluids:

A sensitivity analysis was performed to know how the variation in viscosity changes the volume of the interface. A pipe with 20" diameter transporting gasoline and kerosene have viscosities 0.64 and 2.71 respectively in a 50:50 transmix.

Gasoline	Kerosene	Transmix volume(bbls)
Viscosity (cSt)		
0.64	2.30	1429.7
0.64	2.71	1438.6
0.64	2.78	1439.8

Table 5.6 Sensitivity with Viscosity

Increasing the viscosity of the fluid results in the fluid to move slowly and overrun by the fluid with lesser viscosity, leading to an increase in the transmix volume. From (Table 5.6) it can be inferred that if viscosity of a fluid is decreased, it results in reducing the volume of the transmix. So, changing viscosity of the fluid effects the volume of the transmix.

Validating the software:

A pipe with 22" diameter transporting gasoline and kerosene in a 50: 50 mix was used in validating the software. When the program runs, it directly takes the values of kinematic viscosity of gasoline and kerosene from the database. The volume of transmix is calculated at a velocity of 4.5 ft/s. For validation purpose the kinematic viscosity of gasoline and kerosene are directly entered for calculation, which produced the same results as to that of volume of transmix with the values directly entered from the database.

Validation of the transmix length equation given by Austin and Palfrey (1964) in their published paper and from the code of the present study: Gasoline and Kerosene are sent as a batch, having the following specifications:

Pipe diameter = 16 inches

Distance travelled by interface = 1,000,000 ft.

	Austin and Palfrey (code)	Austin and Palfrey (graph)
Reynolds number	354081	350000
Interface length (ft.)	3691	3600
Interface volume (gal)	35023	35000

Table 5.7 Validation at 16” diameter

Pipe diameter = 12 inches

Distance travelled by interface = 5,000,000 ft.

	Austin and Palfrey (code)	Austin and Palfrey (graph)
Reynolds number	338155	335000
Interface length (ft.)	7355	7400
Interface volume (gal)	43214	42000

Table 5.8 Validation at 12” diameter

(Table 5.7) and (Table 5.8) give almost the same values for the interface length.

CHAPTER VI

CONCLUSIONS

When two fluids, upstream and downstream are flowing in a batch, mixing occurs at the leading end of one batch and trailing end of the other. This is called transmix. Transmix varies in concentration along the length of the pipeline. Austin and Palfrey (1964) have established an equation to estimate the interface length along the length of pipeline. The turbulent region given by Austin and Palfrey (1964) equation can be divided based on the critical Reynolds number of the turbulent regime. In the region above the critical Reynolds number in the turbulent regime, interface length increases slowly with increasing Reynolds number, where as in the region below critical Reynolds number, interface length decreases rapidly with increase in the Reynolds number.

The equation given by Austin and Palfrey (1964) is dependent on some of the parameters such as distance travelled in the pipeline, pipe diameter, Reynolds number, average velocity of flow of the fluid in the pipeline, kinematic viscosity, mass fraction and density. In the present study software was developed to estimate the transmix volume and a sensitivity analysis was performed to discern how the above parameters affect the transmix volume. The following facts have been established performing the sensitivity analysis, they are:

1. Volume of transmix and length of the interface increases along the length of the pipeline. As mixing increases along the length of pipeline, the axial dispersion coefficient increases resulting in an increase in transmix volume.
2. When a fluid is sent in a pipe with constant diameter, length of the interface decreases with the increase in the velocity of the fluid flowing in the pipeline. This can be attributed to the boundary layer thickness near the wall of the pipeline which results in the increase of the transmix volume when the fluid is flowing at low velocities. A velocity of the fluids at 5 ft/s to 7 ft/s is recommended to decrease the amount of transmix volume in the pipeline.
3. Transmix volume of the batch remains constant if the mixture is taken as 50:50 mix even though the leading and trailing fluids are interchanged. If a high viscous liquid is flowing downstream, it moves slowly resulting in mixing with the leading end of the other batch increasing the transmix volume. Mass faction of the high viscous downstream fluid should be less to decrease the transmix volume.
4. When the downstream fluid is a high viscous fluid, volume of transmix increases slightly when the viscosities of fluids in the batch are similar and increases rapidly when there is a difference in viscosities.
5. Transmix volume of the batch increases with an increase in viscosity of one fluid.

For future studies secondary factors such as friction coefficient, difference in density, absolute roughness can also be attributed to the increase in transmix volume.

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APPENDIX A

MODEL EQUATIONS FOR INTERFACE LENGTH

Pipelines are used in transporting the fluids from the gathering systems to the point where it has to be delivered. So almost the same pipelines are used in transporting the fluids of different qualities and characteristics in a series. When the fluids (1 and 2) are sent in series, mixing occurs at the interface diminishing the quality of the liquid with high grade.

According to Taylor (1954) two fluids (1 and 2) having equivalent viscosities and fluid1 is primarily sent into the circular pipe .After a certain time period fluid 2 is sent into the circular pipe. Fluid 1 is the downstream fluid and fluid 2 is the upstream fluid. At time t = 0 fluid 2 enters the pipe at one end x = 0 and pushes fluid 1 along the circular pipe. At a particular length in the circular pipe fluids start mixing. According to Taylor (1954),

The mass diffusion equation is:

$$\frac{\partial C}{\partial t} = K\frac{\partial^2 C}{\partial x^2} \qquad \text{(A.1)}$$

Where C is the concentration, K is the axial dispersion coefficient, x is the length of the pipe and t is the time.

Solving the second order PDE, (Equation A.1)

Boundary conditions are:

At all t: $x = 0: C = C_0$ (A.2)

$x = \infty: C = 0$ (A.3)

Defining a new variable to solve (Equation A.1)

$$\eta = \frac{x}{\sqrt{4Kt}} \qquad \text{(A.4)}$$

Where x is the length of the pipe, K is the axial dispersion coefficient and t is time.

Replacing η from (Equation A.4) in (Equation A.1), we get

$$\frac{dC}{d\eta}\left(\frac{\partial \eta}{\partial t}\right) = K \frac{d^2 C}{d\eta^2}\left(\frac{\partial \eta}{\partial x}\right)^2 \qquad \text{(A.5)}$$

Solving (Equation A.5), using the differential of η w.r.t x and t in Equation (A.4), we get

$$\frac{d^2 C}{d\eta^2} + 2\eta \frac{dC}{d\eta} = 0 \qquad \text{(A.6)}$$

(Equation A.6) represents the conversion of second order PDE (Equation A.1) to second order ODE (Equation A.4)

The boundary conditions given by (Equation A.2) and (Equation A.3) are converted to

At $\eta = 0$: $C = C_0$ (A.7)

$\eta = \infty$: $C = 0$ (A.8)

Defining a new variable y to convert the second order ODE to first order ODE.

Let $\frac{dC}{d\eta} = y$ (A.9)

Substituting (Equation A.9) in (Equation A.6)

$$\frac{dy}{d\eta} + 2\eta y = 0 \qquad \text{(A.10)}$$

Or $\frac{dy}{y} = -2\eta(d\eta)$

Solving (Equation A.10), we get

$$\ln y - \ln a = -\eta^2$$

$$y = a \exp(-\eta^2) \tag{A.11}$$

Where a is a constant.

Substituting (Equation A.9) in (Equation A.11)

$$\frac{dC}{d\eta} = \mathrm{a}.\exp\left(-\eta^2\right) \tag{A.12}$$

Solving the differential (Equation a.12), we get

$$C = a.\int_0^{\eta} \exp(-\eta^2)\,d\eta + m \tag{A.13}$$

Applying the boundary condition given by (Equation A.7) and (Equation A.8)

At $\eta = 0$

$$C_0 = a.\int_0^{0} \exp\left(-\eta^2\right)d\eta + m \tag{A.14}$$

$$C_0 = k$$

At $\eta = \infty$: $$-C_0 = a.\int_0^{0} \exp\left(-\eta^2\right)d\eta \tag{A.15}$$

Where C_0 is the initial concentration, a and m are constants

Error function $erf\ (x)$ can be defined by:

$$erf\,(x) = \frac{2}{\sqrt{\pi}}\int_0^{x} \exp(-x^2)\,dx \tag{A.16}$$

Substituting (Equation A.16) in (Equation A.14) results in,

$$a = \frac{-C_0}{\sqrt{\pi}/2} \quad (A.17)$$

Substituting the value of a in (Equation A.15)

$$C = \frac{-C_0}{\sqrt{\pi}/2} \int_0^{\eta} \exp(-\eta^2) d\eta + C_0 \quad (A.18)$$

Substituting the error function (Equation A.16) in (Equation A.18) we get,

$$C = \frac{-C_0}{\sqrt{\pi}/2} \left(\frac{\sqrt{\pi}}{2} \right) erf\,(\eta) + C_0 \quad (A.19)$$

Solving (Equation A.19)

$$C = C_0(1 - erf(\eta)) \quad (A.20)$$

Substituting $\eta = \frac{x}{\sqrt{4Kt}}$ in (Equation A.20)

$$C = C_0\left(1 - erf\left(\frac{x}{\sqrt{4Kt}}\right)\right) \quad (A.21)$$

Assuming that the length of the interface to be of length S/2 for the fluid ranging from $0.01 < C < 0.98$. Let the concentration of the interface be 0.5.

Equation 3.44 can be written as

$$0.01 = 0.5\left(1 - erf\left(\frac{x}{\sqrt{4Kt}}\right)\right) \quad (A.22)$$

Solving for (Equation A.22)

$$0.98 = \left(erf\left(\frac{S}{4\sqrt{Kt}}\right)\right) \quad (A.23)$$

From the table of error function: $erf\ (1.645) = 0.98$ (A.24)

Substituting (Equation A.24) in (Equation A.23), we get

$$\frac{S}{4\sqrt{Kt}} = 1.645 \quad \text{(A.25)}$$

$$S = 6.58\sqrt{Kt}$$

$$S = 6.58\sqrt{\frac{KL}{U}}$$

Where S is the length of the interface, K is the diffusion coefficient is the total residence time of the fluids in the pipe at a length of L and average velocity of U.

APPENDIX B

EMPIRICAL CORREATIONS FOR INTERFACE LENGTH

Jablonski (1946)

$$S = d^{0.4} L^{0.6} \left(1.5169 + \frac{20281.1}{\mathrm{Re}}\right) \left(\frac{Max(\rho_a, \rho_b)}{Min(\rho_a, \rho_b)}\right) \qquad \text{(B.1)}$$

Where S is the length of interface, d is the inner diameter of pipe, Re is the Reynolds number , ρ_a is the density of fluid a and ρ_b is the density of fluid b.

Birge (1947)

For a gasoline – gasoline interface:

$$S = 0.9944345 \ L^{0.482} \qquad \text{(B.2)}$$

For a gasoline-kerosene interface:

$$S = 1.10288 \ L^{0.529} \qquad \text{(B.3)}$$

Smith and Schulze (1948)

$$S = L^{0.62} \left(0.55 + \frac{1075}{\mathrm{Re}^{0.87}}\right) \qquad \text{(B.4)}$$

Taylor (1954):

$$S = 6.59998 \ \mathrm{Re}^{-0.0625} \sqrt{dL} \qquad \text{(B.5)}$$

Sjentitzer (1958)

$$S = 245.999\, d^{0.43} L^{0.57} \,\mathrm{Re}^{-0.45} \tag{B.6}$$

Austin and Palfrey (1964)

For $\mathrm{Re} > 10000 \exp\left(1.52\sqrt{d}\right)$ (B.7)

$$S = 11.75\,\mathrm{Re}^{-0.1} \sqrt{dL} \tag{B.8}$$

For $\mathrm{Re} \leq 10000 \exp\left(1.52\sqrt{d}\right)$ (B.9)

$$S = 18420\,\mathrm{Re}^{-0.9} \sqrt{dL} \exp\left(1.21\sqrt{d}\right) \tag{B.10}$$

Udoetok & Nguyen (2009)

$$n = \frac{1}{\sqrt{f}} \tag{B.11}$$

$$S = \left(1 - \left(1 - \left(\frac{2n^2}{(n+1)(2n+1)} \right)^n \omega^n \right)^2 \right) L \tag{B.12}$$

n signifies the effect of pipe roughness on interface extent at the walls.

ω is an experimental constant and has a value of 0.585 based on the field data by Udoetok and Nguyen.

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