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Numerical Investigation of the Transition Length at the Entrance Region of Pipe Flows

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Abstract: In this study, the steady, incompressible and axis symmetric flows in the pipe entrance region has been simulated numerically for the Reynolds numbers between 1000 and 25000 and for the square edged pipe inlets. The developing boundary layer at the pipe entrance region first grows as laminer then disturbed to a turbulent state at downstream away of the inlet. From pipe inlet to a downstream distance where laminer to turbulent transition begins is called the transition length. Determination of the transition length has been significiant for hydro and aeromechanics and yet it seems not to be defined clearly. The effects of wall surface roughness, pipe diameter and Reynolds numbers on transition length has been investigated numerically by covering transition and turbulent flow regimes too. On the purpose, water flows were simulated numerically including five different relative roughness. The numerical results obtained has shown that the transiton length is the power function of the Reynolds number inverse proportionally. Likewise the numerical study has also shown that changing the pipe diameter but keeping the relative roughness the same has left no effect on the transition length. As an outcome, a numerical correlation which define the dimensionless transition length and well fitting the numerical values was derived as a function of Reynolds number.

Keywords: Entrance length, Pipe flow, Developing flow, Numerical

Introduction

In 1800, Osborne Reynolds has found the flows behaving as two different in the experiments he made then the flow is classified as laminer and turbulent. Laminer flow is a kind of flow that occur at low velocities and follow a regular movement whereas turbulent flow is a kind of flow that occurs at bigger velocities than low and is a kind of irregular and intermixed flow. He found the dimensionless Reynolds number to specify the flow type. Laminer flow is a stable flow and effects such as vibration, free stream turbulence and roughness disturb the flow stability and make the flow turbulent. It has been seen in many experiment that the flow can stay laminer when a sensitive flow condition was provided (Özışık M. Necati (1985), White F.M. (2003)). When osborne Reynolds mix the flow at pipe entry to make turbulence, laminer flow lasted up to a Reynolds number of 2300 and when a sensitive flow condition was provided by not allowed to any turbulence exists it has been seen that laminer flow lasted up to a Reynolds number of 13000 in the experiments.

For the flows over a flat surface, flow first begins as laminer in the leading edge and a certain distance away from the inlet the flow stability is deteriorated and it become a turbulent flow structure. Figure 1 illustrate three stages of the fluid flowing over the inside surface of a pipe as being laminer, transient and turbulent. The flow distance from the pipe inlet to the location where the flow first disturb to turbulent is called the transition length *(L_t).* After tarnsition length, a transitional flow region ocur for a while then the flow becomes fully developed. The measured distance from inlet to where the flow to become full turbulent is called entrance length. It is seen in many experimental works that the flow distances is depend on the flow velocity, surface roughness, free stream turbulence level, surface vibrations, and heating and cooling processes (Minkowycz et al. (2009), Zanoun et al. (2009)). Though some empirical correlations are proposed for both flow distances through the

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experiments, a general solution to the problem is not still be clarified well due to many parameters effects on the flow.

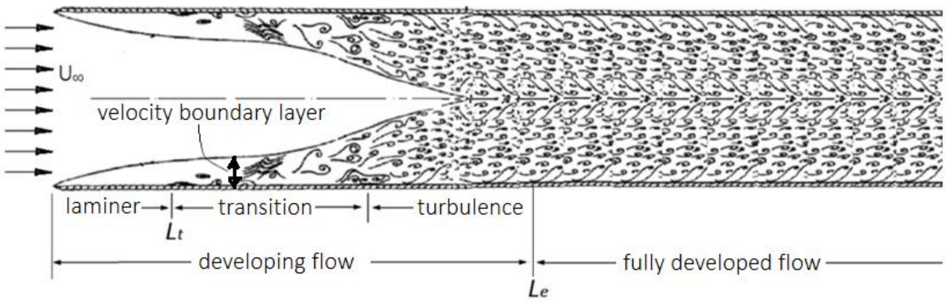

Figure 1. Developing and fully developed flow at pipe entrance

According to experimental studies, when a flow with high freestream turbulence level pass over a full roughly surface, transition length lasted up at $Re_t = 10^5$ but for a flow not contained any tubulence in the freestream pass and over a smooth flat surface it lasted up to $Re_t = 10^6$ *as measured in the experiments* (Özışık (1985)). In case pipe inside flow study, due to pipe diameter limit the flow peripheral , transition distance from laminer to turbulence is being different than the flows over flat surfaces. Fig. 2 has shown the flow development after pipe inlet. The velocity boundary layer that forms the result of the viscous effects from the pipe inlet, thickness of it increase along the inlet and since the thickness is limited by the pipe radius, the entire flow cross-section is filled with the boundary layer. From the pipe inlet, the viscous effects begin to change in the resulting velocity profile. This velocity profile changes along the flow until it become a constant velocity profile. The flow region where the velocity profile changes is called inlet flow or developing flow. The pipe flow, in which the velocity profile is along constant, is called the fully developed pipe flow. Different definitions are also available in the literature for fully developed pipe flow. For example, fully developed flow begins when such like two flow properties, wall shear stress or mean turbulent flow statistics reach the constant values (Anselmet et al. (2009), Patel&Head (1969)). Therefore, Zimmer et al. (2011) said that it should be required to define the fully developed flow as a flow that starts when the time-averaged turbulence flow statistics become constant. In the author's experimental study, it was reported that the developing flow distance is even longer when turbulence flow statistical values was measured.

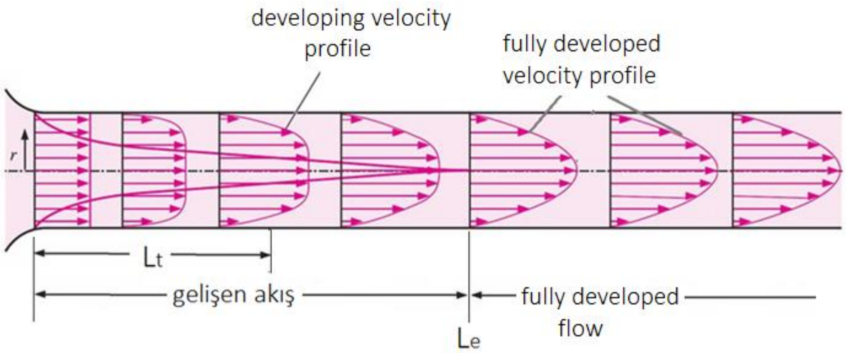

Figure 2. Variation of velocity profile along the developing and fully developed flow

Along the fully developed pipe flow, the wall shear stress and the friction factor are constant since the pressure drop is linear. The fully developed laminar or turbulent pipe flows are largely solved with theoretical and empirical relations, while the developing flow portion has still not been fully solved. In engineering applications, pipe-tank connections generally become conical (bell mouth), square edged and reentrant. while a sharp edged inlet produce much turbulence in the flow, bell mouth inlet produces minimal turbulence. The amount of turbulence goes to pipe at the inlet is effect on the transition and entrance lengths (Tam et al. (2013), Augustine (1988)). It is evident that the transition and inlet lengths with high turbulent inlet are shorter than with the low turbulent inlet. Table 1 gives the entrance lengths reported in experimental studies of pipe flows.

As shown in Table 1, the dimensionless entrance lengths (L_e / D) are reported for a large Reynolds number range for the turbulent flows. The experimental studies reported have also not been performed especially to measure entrance lengths, they are measured additionally in the experimental studies for different purposes. In most of these experimental studies, the pipe inlet connection type used is not reported. According to Table 1 the inlet lengths vary from 25 to 80 diameters. It appears well from the Table 1 that the the empirical relations expressing the entrance lengths is also suggested. Anselmet et al (2009) has reported two empirical relation at high Reynolds numbers as given in Table 1 and also it appear that Augustine (1988) has suggested an empirical relation. It is seen in the literature that experimental studies on pipe flow are mainly aimed at finding the inlet lengths. Experimental studies to find transition lengths are rare. In this study, the transition lengths were investigated numerically in the Reynolds numbers range of $2x10^3$ - $25x10^3$. The flow at the inlet of the pipe was chosen with a smooth velocity profile and at high turbulence intensity. The numerical results obtained are analysed and compared with empirical data. As an outcome, two numerical relation expressing the transition lengths are developed.

Numerical Pipe Flow

Firstly, in order to gain validation to numerical solution, an experimental study has been carried out with four pipe types made of different materials. Pipe types, relative roughness and pipe diameters are given in Table 2. Here it is aimed to see the effects of different relative roghness on flow conditions. The relative roughness of the tubes given in Table 2 was determined by the pressure differences measured in the fully developed flow region in the experiment.

Table 1. Dimensionless entrance lengths reported by the experimental studies

Dimensionless Entrance Length (L/D)		**Reynolds Number**	**Author**
Constant wall shear stress	**Mean turbulent statistics**		
80		-------------	Osborne Reynolds
$L_e/D = 2.09x10^{-8} *Re^{-1.66}$		5000-15000	Augustine (1988)
$L_e/D = 1.6\ Re^{1/4}$		10^5 - 10^6	Anselmet et al. (2009)
$L_e/D = 4.4\ Re^{1/6}$			
A long Empirical formula		1,95 x 10^5	Salami (1986)
25 - 40		$3x10^3$ - $3x10^6$	Nikuradse (1966)
30		$5x10^4$ - $5x10^5$	Laufer (1954).
50 - 80		10^3 - 10^4	Patel & Head (1969)
70		$3x10^4$ - $1x10^5$	Zanoun et al. (2009)
--------	72	175000	Perry & Abell (1978)
50	80	$1x10^5$ - $2x10^5$	Doherty et al. (2007)
Not attain to 40		388000	Barbin&Jones (1963)
	70	$1.5x10^5$- $8.5x10^5$	Zimmer et al. (2011)

Table 2. Pipe type, Relative roughnesses and diameters

Pipe Type	**Diameter**	**Relative roughness**
	(mm)	ε / D
Aluminium pipe	26	0,0016
Copper Pipe	26	0,00016
Steel Pipe	28	0,0024
Galvanized Pipe	28	0,0026
PPRC pipe	21	0,00033

Static pressures were measured trough piezometres tubes fitted on pressure taps, which is welded to the holes drilled at seven different locations on the pipe. Pipe flows at each flow rate were recorded bya camera for three minutes. Time mean values of pressures are obained for each location from each flow record. The pressure values obtained from the numerical flows made in the same parallel with the experiment are compared with the pressure values measured in the experiment in Fig.3.

Numerical Solution and Validation

Basically, fluid flows are defined by differential flow equations which is the results of the laws of mass, momentum and energy conservation. For this reason, the flow field in turbulent flows shows a continuous change with time temporarily and spatially. The time-dependent solution of a turbulent flow is difficult since it requires a solution to the time-dependent development of turbulence structures that is available in a wide range in the flow. The numerical method used to solve the time-dependent fundamental flow equations of a turbulent flow is called direct numerical simuation (DNS). The solution is not possible with today computers except that of very simple flows. Since solution is required very large mesh numbers and time steps.

An another method suggested for the solution of turbulent flow is to take the instantaneus effects of the flow to the time average effect. By this way, turbulent flows become time independent flows. The instantaneous drags existed by the turbulent structures against the flow form additional stresses in the time-averaged basic flow equations. These stresses are called Reynolds stresse or turbulent sresses. The time averaged conservation equations that forms in this way are called Reynolds averaged Navier-stokes equations (RANS). The only unknown in RANS equations is the Reynolds stresses. Therefore many turbulence models are developed to solve these Reynolds stresses. The solution of a turbulent flow with RANS equations is simple and the cost of numerical computation is very low in comparison to the DNS method.

In this study, turbulent pipe flows are solved via computer by applying finite difference numerical method to RANS equations. SST k-omea model are selected to solve the Reynolds stresses. To provide laminer to turbulent transition, Gamma-Theta model is selected. The pipe length has been selected long enough to cover the fully developed flow partly. Since the pipe flow is axis symmetrical, the flow area is limited to a small flow area sliced. The boundary conditions, fluid properties and flow type are defined in Table 3 below.

Table 3. Boundary conditions and flow field properties

Numerical properties	
Flow state	Steady-state, incompressible and isothermal flow
Basic flow equations	RANS Equations
Turbulence model	SST k-omega model
Pipe inlet	Smooth velocity and high turbulent intencity $(T_U) = \%7$
Pipe wall	roughly
Pipe outlet	Open to atmosphere at gauge pressure
fluid	27 ^{o}C water

As shown in table 3, after setting up of boundary condition, flow and fluid properties, pipe flows are solved with CFX flow solver program. Numerical flows are kept parallel with experimental flows. As a result, the flow characteristics such as pressure, velocity, friction factor and wall shear stress were analyzed along the flow. Numerical and experimental values were compared in order to gain validity to numerical solution. The experimental and numerical values are compared in Fig 3 in terms of the pressure drop across the flow including all the flows of a pipe type. As shown in Fig. 3, experimental values and numerical values are agree well to each other. The mean and maximum deviations of the numerical values from the experimental ones are given in Table 4.

As can be seen in Table 4, numerical values of all pipe flows deviate from the experimental values by 7-9% about on average. The deviation amount is a tolerable one since it is natural to have such a detective. Because physical conditions such as fluid temperature can not be precisely determined and faults that occur in flow measurements and in static pressure readings in experimental runs are thought to be caused by these deviations. For this reason, flow characteristics are analyzed below using numerical data.

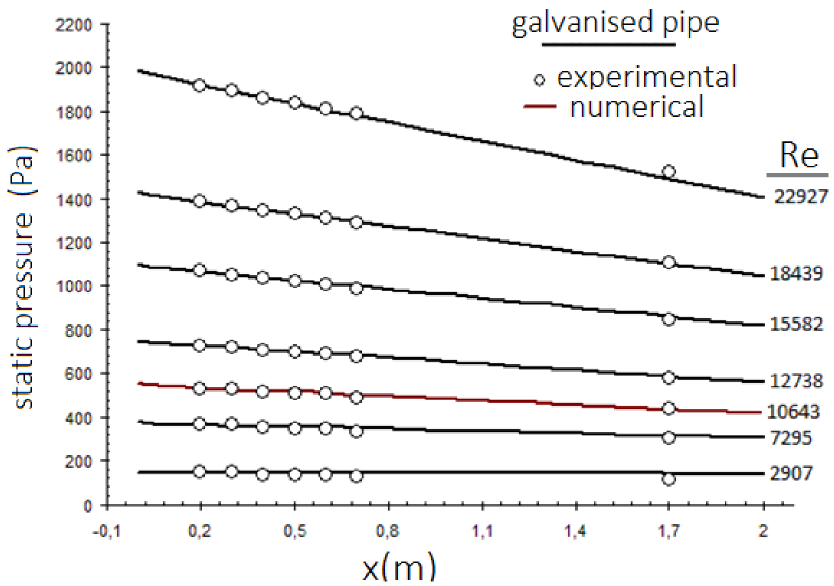

Figure 3. Coparison of numerical and experimental data in terms of pressure variation along the flow

Table 4. Percent deviation of numerical values from experimental data in terms of pressure variation along the flow

Deviation (%)	**aluminium pipe**	**copper pipe**	**commercial steel pipe**	**galvanised pipe**	**Plastic pipe**
maximum	±%20	±%24	±%36	±%35	±%18
average	%7.30	%7.70	%7.60	%9.40	%9

Numerical Analysis

Transition values must be obtained from the numerical solution so to analysis the transition distance. As the flow properties change at location where laminar to turbulence transition occur, the transition distance can be obtained from that flow characteristic which show the best in change at location. Variation of velocity, friction factor and wall shear stress in the transitional flow can be examined. Pressure variation along the pipe entrance is commomnly determined in experimental flows in order to find the transition distance. Since the wall shear stress or friction factor associated with the pressure variation change more distinctive therefore the transition distances can be obtained from the Darcy friction factor variations. The relationship between wall shear stress, pressure change and Darcy friction factor can be found by the static force balance on the Δx differential wall flow include pressure drop.

$$\tau_d = \frac{1}{4}\frac{D}{\Delta x}\Delta P = \frac{D}{4}\frac{\partial P}{\partial x} \qquad (1)$$

$$\Delta P = f * \frac{\Delta x}{D}\frac{1}{2}\rho U^2 = f * \frac{\rho U^2}{2D} \qquad \tau_d = \frac{1}{8} f \rho U^2$$

Where ΔP is the static pressure difference that occurs at the pipe flow portion with a thickness of *Δx*. *U* is the average flow velocity in the pipe and *f* is the Darcy friction factor. As can be seen, the wall shear stress and the friction factor are functions of the pressure gradient. Since the pressure drop is linear in the fully developed flow, the pressure gradient becomes constant so that the wall shear stress and the friction factor are also constant. Since the pressure drop in the developing flow region is parabolic, the shear stress and friction factor are variable here.

Figure 4 show the variation of the wall shear stress along the flow which is obtained from the numerical solution. As can be seen from the figure, wall shear stress has shown a parabolic change at the entrance of the pipe. This variation show the developing flow at pipe entrance. Wall shear stress is increasing after a minimum value. The reason why start to increase after a minimum is that the flow begins to gain turbulence. After a certain distance the shear stress will no longer change. Unchanged values sign to a fully developed flow. The flow section where the wall shear stress no longer changes is called fully developed flow. Since many experimental studies show that the pressure drop is linear in the fully developed flow region, so that the wall shear stress is constant in this flow region. The location where the wall shear stress becomes minimum is the location where the laminer to turbulence is first begin to transit. For this reason, the transition distances are obtained from measuring the flow distances where the minimum values exists. For example in aluminum pipe, the variations of friction factors are shown in Fig.5 for different Reynolds numbers. On observing the friction factor curves in the Figure 5 it is seen that the minimum distance becomes shorter towards high Reynolds numbers. Here, the laminar flow region narrows and fully developed flow begins to occur at the short pipe distances. This shows that the transition distance is getting smaller towards high Reynolds numbers. The transition distances at each flow rate found from the numerical Darcy friction factor variations are given in Table 5.

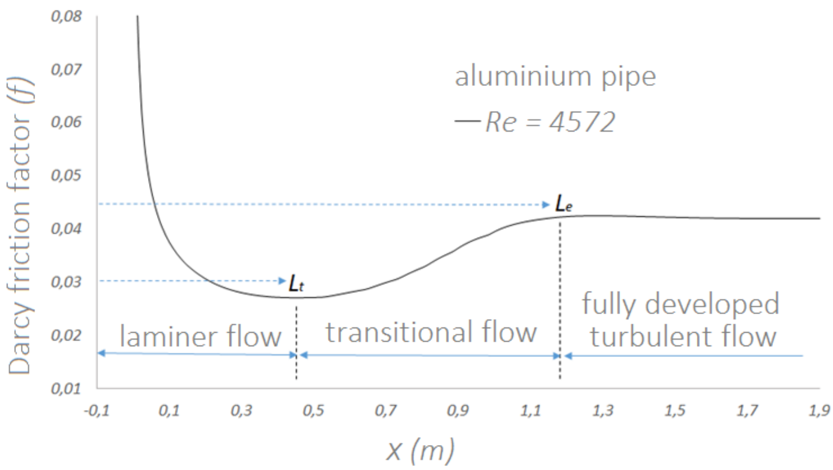

Figure 4. Variation of Darcy friction factor along the pipe flow

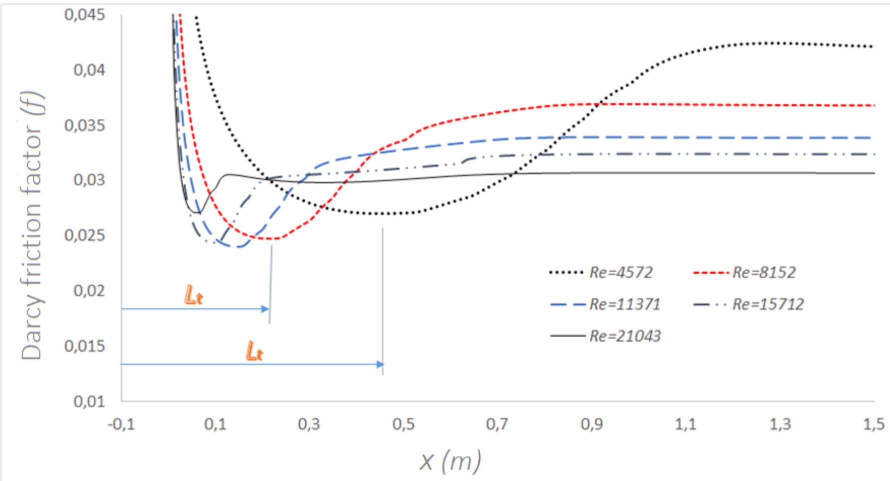

Figure 5. Variation of Darcy friction factor along the flow at different Reynolds numbers

Table 5. Numerical transition lengths obtained from the flows at different Reynolds numbers of five pipe types

	Aluminium pipe									
Reynolds	**4572**	**5539**	**8152**	**9496**	**11371**	**12172**	**15712**	**18004**	**21043**	
L_t (m)	0,419	0,354	0,202	0,169	0,139	0,124	0,093	0,078	0,061	
	Copper pipe									
Reynolds	**3443**	**4326**	**5738**	**7785**	**9282**	**11079**	**13295**	**15856**	**18387**	**21077**
L_t (m)	0,652	0,460	0,326	0,224	0,184	0,150	0,122	0,098	0,082	0,071

	steel pipe										
Reynolds	**3609**	**5422**	**7101**	**8722**	**10643**	**11906**	**13907**	**17257**	**19733**	**21688**	**23602**
$L_t\,(m)$	0,611	0,356	0,252	0,192	0,156	0,132	0,110	0,084	0,071	0,060	0,050
	galvanised pipe										
Reynolds	**4559**	**7295**	**9553**	**10643**	**11977**	**14078**	**15582**	**18439**	**22927**		
$L_t\,(m)$	0,449	0,234	0,180	0,150	0,130	0,109	0,094	0,072	0,051		
	PPRC plastic pipe										
Reynolds	**3691**	**4921**	**6890**	**8120**	**9843**	**12890**	**14458**	**17540**	**20979**	**24317**	
$L_t\,(m)$	0,468	0,310	0,214	0,165	0,139	0,096	0,084	0,071	0,058	0,048	

When Table 5 is observed, it is seen that the transition values decrease with Reynolds number. The transition values of the plastic pipe flow are lower than other pipe flows. The only reason is that the flow velocity in the smaller pipe diameter is bigger than other pipes. Therefore, high flow velocity cause to laminer to turbulence transition becomes earlier. Since flow velocity is a very effective parameter on the flow stability to breakdown. The variation of the dimensionless values (L_t / D) of the numerical L_t values, obtained for each flow rate as shown in Table 5, are illustrated in Fig. 6. across Reynolds numbers. As shown in Figure 6, the variation of L_t / D values conform to an exponential function inversely proportional to the Reynolds number. When the dimensionless transition distances of five pipes are examined, it is seen that the effect of relative roughness on L_t values is seen in a level to negligible when compared to Reynolds number effect. Curve fitting operations were performed to derive a general relation to the variations of the dimensionless transition values given with Reynolds number. As a consequent, it is seen that the dimensionless L_t / D curves fit well with both relations given in Equ.2 and Equ.3.

$$\frac{L_t}{D} = 406429\left[(\mathrm{Re} - 2000)^{-1.215} - 2700\,\mathrm{Re}^{-2.2}\right] \tag{2}$$

$$\frac{L_t}{D} = 619062\ \mathrm{Re}^{-5/4} \tag{3}$$

As shown in Fig. 6, Equ. 2 has shown a deviation of ± 25% in maximum and a deviation of ± 10% in average from the non-dimensional numerical transition values. Equ. 3 has shown a deviation of ± 20% in maximum and an deviation of ± 8% in average from the numerical non-dimensional transition values. Both of the proposed equations also express well the dimensionless numerical transition values. In the numerical study, it is shown that the dimensionless transition values are very close to each other despite the use of pipes in different relative roughnesses. According to the experimental studies reported, the most effective parameter on the transition values is the Reynolds number, which is a representative to the flow velocity, and the free stream turbulence. In the numerical study, high turbulence level (7%) was entered at the pipe inlet. For this reason, the transition values found in this study will be shorter than for a low turbulence inlet, as long as the same pipe and Reynolds number are considered. Since the turbulence amount at the pipe inlet is being very effective on the laminer to turbulence transition. So in an inlet containing high turbulent intensity, the transition distances will be lower

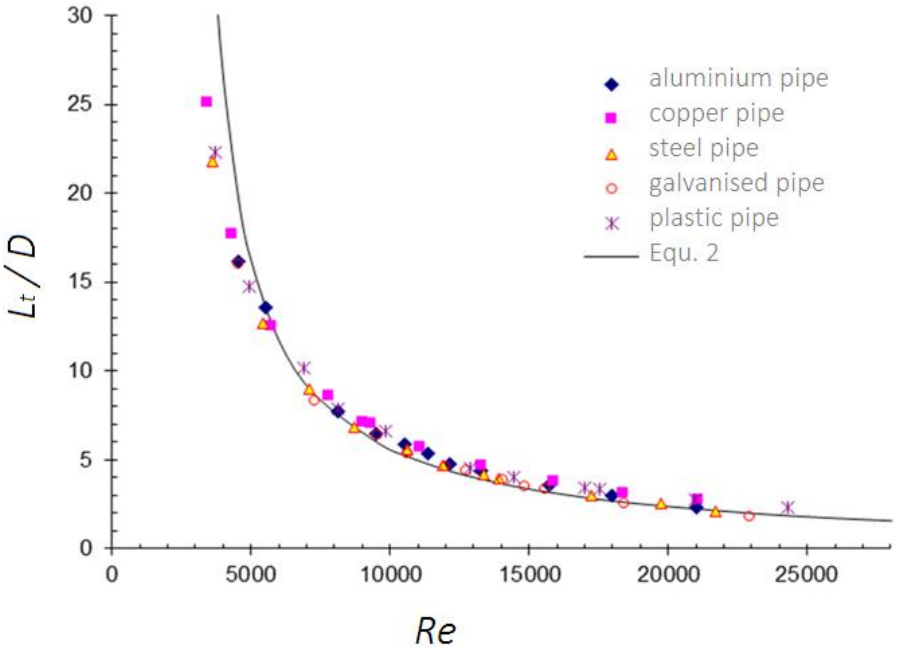

Figure 6. Variation of dimensionless transition lengths with Reynolds

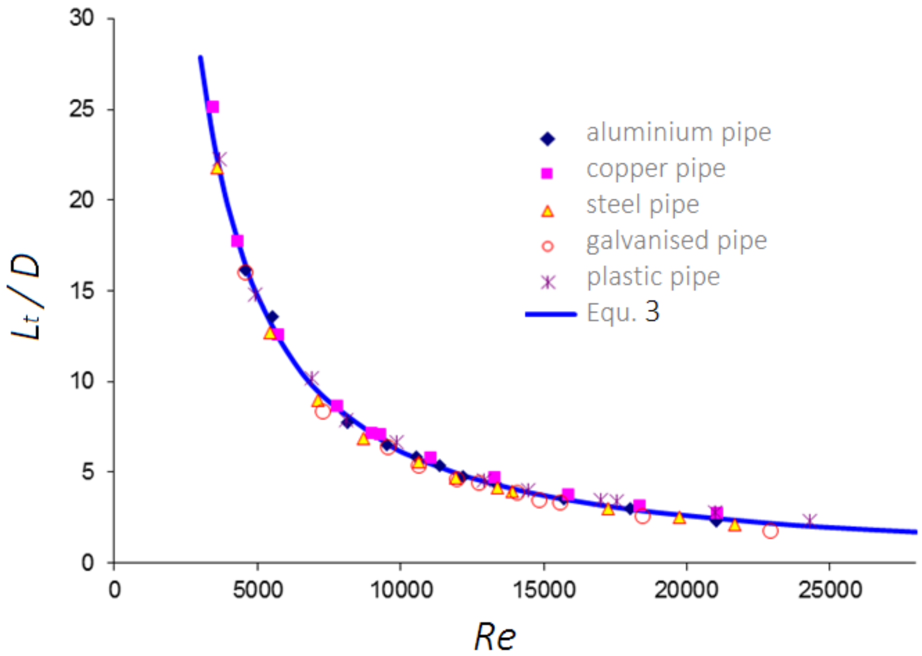

Figure 7. Numerical variation of transition lengths with Reynolds

Here, an additional numerical flow simulations were carried out to investigate the influence of relative roughness on the transition distance. Pipe diameters are changed while the relative roughness remained the same in all runs of the numerical flow simulations. Numerical flows were performed by using two different relative roughness values. The variation of the transition values, obtained from the new numerical solutions, with Reynolds numbers are shown in Fig. 8 dimensionlessly.

As shown in Fig. 8, it is seen that on observing the variation of the dimensionless transition values with Reynolds number, the values are fitted on each other for the diameters with the same relative roughness. It is seen that in Figure 8, the dimensionless transition distance in the pipes with high relative roughness is lower than in the pipes with low relative roughnesses. The difference seems slightly higher towards high Reynolds numbers. The transition values of both relative roughnesses in the same Reynolds numbers can be compared as a percentage. While it is seen that the dimensionless transition value at low relative roughness (ε / D = 0,00033) is 6% higher than the transition value at high relative roughness (ε / D = 0,0026) at Re = 4000, it is also seen

%4 at Re = 8000 , %19 at Re = 16000 and %39 at Re = 20000. One reason for the shortened of the transition distance in the pipes where the relative roughness is high is that the roughness produce turbulence so that the laminer to turbulent transition exists earlier at short flow distances. The reason of the difference decreasing towards low Reynolds numbers is that may be the roughness not being effective on laminer flow or due to low velocity in low Reynolds numbers. So it seems that the relative roughness is being more effective at high Reynolds numbers.

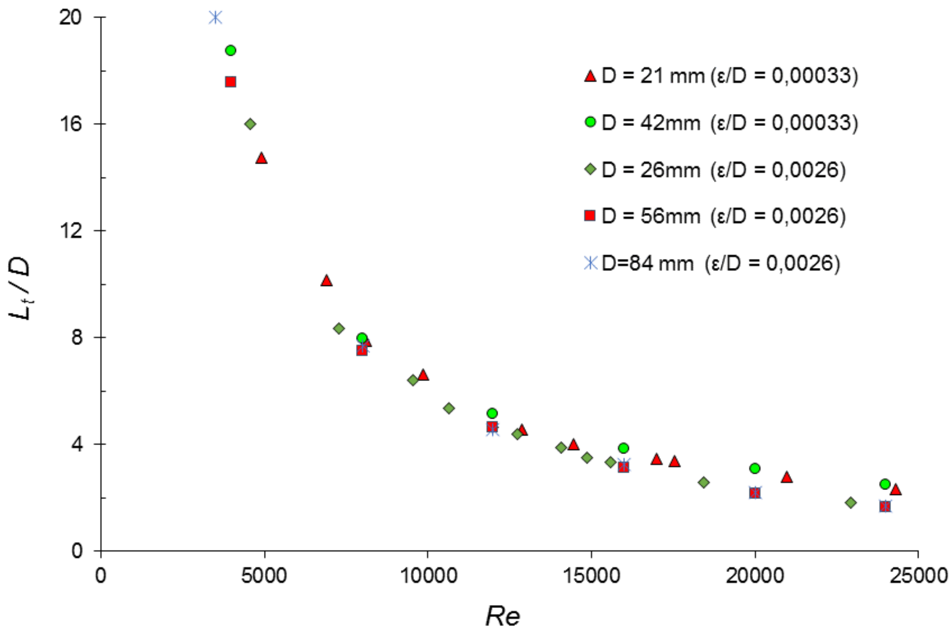

Figure 8. Variation of transition lengths across pipe diameters for the same relative roughnesses

As a result, as shown in Fig. 8, according to the numerical flow analysis made with the pipes in different relative roughnesses, the relative roughness does not seem to have much effect on the dimensionless transition lengths towards low Reynolds numbers however the effect is increased towards high Reynolds numbers. In Figure 8 according to the relative roughness change, it is seen that the difference in transition lengths increases towards high Reynolds numbers. It can be seen here that when the relative roughness increases, the transition distance is beginning to decrease. It is seen that of the pipe diameter variations in the same relative roughness are not effective on the transition values. As a result, it can be seen that in the numerical flow analyzes performed in the range of 3000 to 25000 Reynolds, the dimensionless transition values can be expressed by Equ. 2 and Equ. 3 being well agree.

Conclusion

In this study, the transition distance at which the transition from laminer to turbulence begins is analyzed in the range of 3000 < Re < 25000 Reynolds number in the numerical flow simulations with different relative roughness pipes. Flow simulations are carried out with RANS equations. A high turbulence (7%) value was entered into the inlet flow, to resemble a sharp-edged pipe inlet.
Variation of dimensionless transition distance in flows with Reynolds number, relative roughness and pipe diameter were investigated.

- Transition distance is found as an exponential function of inverse proportion to the number of Reynolds numbers.
- The variation amount in the transition distance decreases towards high Reynolds numbers.

- The effect of roughness on the transition distance has been negligible in comparison to Reynolds effect. When the Reynolds number increases, the influence of the relative roughness variation on the transition distance is increased. The reason is that the roughness produces more turbulence when the flow velocity increases.
- The dimensionless transition distance has changed inverse proportionally with the relative roughness value and not changed when the pipe diameter is changed in the case the relative roughness value remained the

same. Due to the effect of relative roughness on the dimensionless transition distance is low the dimensionless transition distance is expressed as a function of the Reynolds numbers.

As a result of curve fittings, it was seen that the variations of dimensionless transition distances with Reynolds number can be expressed in two relations, Eq. (2) and Eq. (3). Both equations estimate the numerical data with a mean error of 10%. Both of the proposed correlations here are limited to a sharp edged pipe inlet and in the Reynolds number range given in the study. In addition, the suggested correlations should be well supported by experimental data.

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