Numerical Computation of Flow Reattachment Lengthovera Backward-Facing Step at High Reynolds Number

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Abstract— **Investigation of flow separation and reattachment length over a backward facing step are such as the subjects of fundamental fluid dynamics research. The purpose this study is measurement of reattachment length on backward facing step. For this purpose, unsteady flow over a step was simulated in a 2-D by using Computational Fluid Dynamic. Then, secondary flow was added to the $\frac{1}{3}$ height of step. In order to, the effect of angles of 15°, 30°, 45° and 90°, expansion ratios of 1.5, 2, 3 and 4, pressure coefficient and Reynolds number with 75000 over backward facing stepwere investigated. To verify the numerical model, the velocity profile using different turbulence models was compared with experimental values in a sudden expansion. The results showed that RNG k-ε turbulent model was selected as the most suitable model to predict recirculation flow over backward facing step. The results of numerical analysis indicated that the reattachment length increase with increasing step angle, expansion ratio and Reynolds number. Also with increasing Reynolds number, when secondary flow is added to $\frac{1}{3}$ height of step, the eddy diameters and the length of recirculation flow zone decrease. Moreover, increasing pressure coefficient led to increasing the reattachment length.**

Keywords— **Unsteady Flow, Expantion Ratio, Reynolds Number, Turbulent modeles, pressure coefficient, reattachment length**

I. Introduction

Modelling is one of the most powerful tools to investigate the problems in engineering and has been widely used during past decades [1-5]. One of the interest subjects of researchers is the separated flow over a backward-facing step that generates a recirculation zone. Recirculation zone is produced by a sudden expansion in geometry channel. The generated reattachment length has depend on Reynolds number and the geometrical parameters such as the step height and the channel height. During the past 30 years, many researches was done about the flow over a backward-facing step [6-9] two-dimensionally simulated flow over the BFS for Reynolds number of 7600. Results of this study showed that the turbulent wall jet affected on structure of flow at downstream of the BFS. [10, 11] numerically investigated turbulent flow passing over 2-D vertical plate. The result showed that length of recirculation flow zone decrease with increasing Reynolds number. [12, 13] studied turbulent flow over step using experimental observation of PIV and CFD. The results of study have good agreement with experimental results for velocity component; streamline flow and complex structure of backward facing flow [14, 15] studied 2-D steady incompressible flow over a backward-facing step as numerically. Results showed that the size of the recirculating regions grows almost linearly as the Reynolds number increases. [16, 17] used sudden expansion as energy dissipater in outlet dams. They analyzed backward fluid flow over step as 2-D with expansion ratio 1:2. The results showed with increasing inlet velocity, the length of recirculation flow increases. [18, 19] used turbulent models to analyze sudden expansion in high Reynolds number. The result shown that turbulent model has good agreement to experimental data. [20, 21] investigated the effect of expansion ratio, slope, intensity turbulence of free flow, the thickness of reattachment length and separated flow using experimental data. The results indicated that the thickness of boundary layer and turbulence of free flow is the effective parameters on reattachment length and separated flow. [22, 23] numerically investigated the effect of step angel and expansion ratio with different Reynolds number on recirculation flow length. The results shown that with increasing step angel, expansion ratio and Reynolds number, the recirculation flow length increase. [24, 25] evaluated the relation of reattachment length, the height of step, and velocity and flow depth on step. [26] experimentally investigated the flow characteristics of a turbulent wall jet over a backward-facing step in an unconfined wind tunnel with an aspect ratio of 8.1 by the PIV and stereo-PIV measurements. The obtained results confirmed the presence of the wall-jet formation on the bottom wall. [27, 28] Studied separated flow in 90° pipe bend under high Reynolds number by k-ε turbulence model. Numerical results showed that flow separation can be clearly visualized in bend with low curvature ratio.

In this paper, the reattachment length of the separated flow in the downstream of step investigated under condition of different hydraulic and geometry using computational fluid dynamics. For this purpose by attention to, any study was not done on the measuring reattachment length with adding secondary flow to the height of step therefore the effect of

Step angle; expansion ratio and Reynolds number are explored on the reattachment length of the separated flow. A schematic of the problem is shown in Fig. 1.

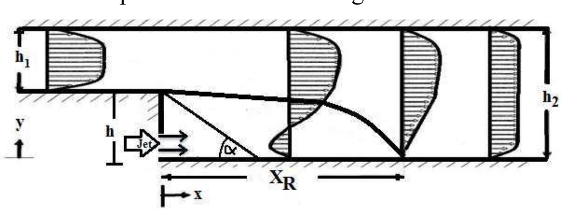


Fig 1. Schematic of a BFS with different inclination angle

II. MATERIALS AND METHODS

In this paper, the experimental data of Eaton and Johnston [1980] were used to numerical simulate the incompressible turbulent flow (water) in a sudden expansion for expansion ratio $\frac{h_2}{h} = 3$.

[8, 29] presented the dimensionless velocity profiles at various sections by experimental investigation of turbulent flow in a sudden expansion. In this study the above mentioned expansion modeled via Fluent and the results are used to verify the bend models. Some part of these result presented.

A. Meshing and boundary conditions

In order to numerical modeling, Second-order upwind scheme was used to discrete all of the equations to achieve higher accuracy in results. Velocity-pressure coupling is established by pressure-velocity correlation using a SIMPLE algorithm and conditions boundary for inlet and outlet are respectively velocity inlet and pressure. Reynolds number based on inlet average velocity and the height of outlet section is 132000. Reynolds number used by other researchers is according to table 1. In present study, it is defined in a $R_e = \frac{U_\infty \times h}{v}$ where U_∞ is inlet velocity, is turbulence viscosity and h is step height.

TABLE1. USED SCALES TO CALCULATE REYNOLDS NUMBER IN DIFFERENT STUDIES LREF =H (STEP HEIGHT) UREF = U_∞

Authors	*Denham&Patich (1974)*	*Armaly et al. (1993)*	*Kaiktsis etal. (1991)*	*Gresho et al.(1993)*	*Adams &Johnston (1988)*	*Present Study*
L_{ref}	h	2 a h	h	(1 + a) h	h	h
U_{ref}	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$
Re	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$	$\frac{2}{3}U_\infty$

The used meshes in order to simulate the flow over back-ward facing step is non-uniform structured that its size is different in some region. In this case the number of meshes are 2250 that it details are illustrated in Fig. 2.

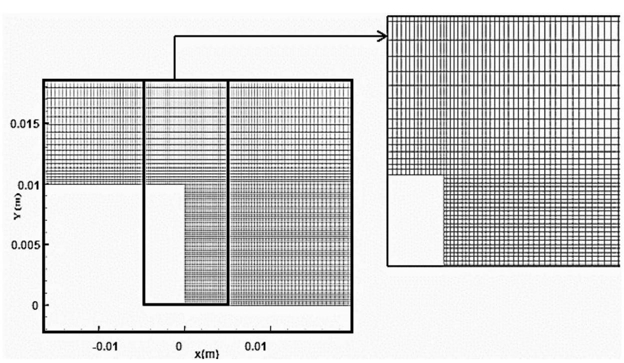


Fig 2. Meshing pattern in the computational domain

To verify numerical model, velocity profile was compared to experimental results in x/h=1.33 according to Fig.3. In this fig u is the longitude velocity and U_0 is the average velocity of inlet. Also y is vertical coordination and h is the step height.

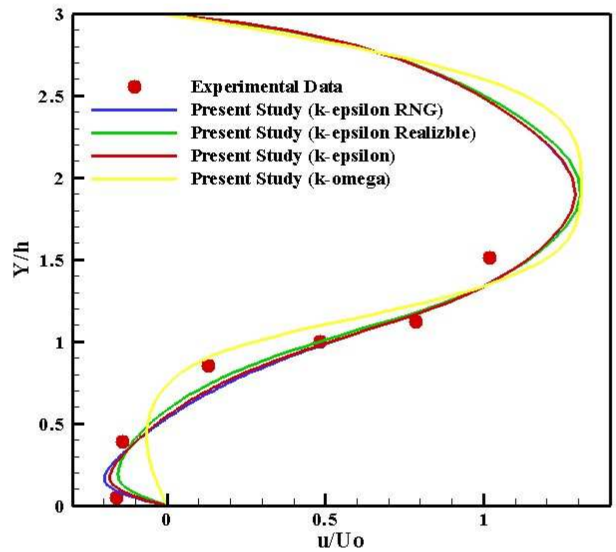


Fig 3. Verification of numerical model

According to Fig.4, it can be concluded that $k-\varepsilon$ (RNG) turbulence model has more accordance to the values of velocity by Eaton and Johnston. Therefore in this study, $k-\varepsilon$ (RNG) turbulence model has been selected as the best computational turbulence model in simulation of circulation flows.

B. A Dimensional analysis

The effective factors on the length of circulation flow zone are: velocity of inlet flow, the height of inlet section, specific mass of fluid, dynamic viscosity, expansion ratio, pressure changes and angle step. Therefore according to Buckingham's theories:

$$\frac{x_r}{h_1} = \frac{x_r}{h_1}\left(\rho, u_0, \frac{h_2}{h}, \mu, \nabla P, \mathrm{h}_1, \theta\right) \quad (1)$$

$$f = f\left(\frac{x_r}{h_1}, \rho, u_0, \frac{h_2}{h}, \mu, \nabla P, \mathrm{h}_1, \theta\right) \quad (2)$$

According to the results of dimensional analysis:

$$\frac{x_r}{h_1} = \frac{x_r}{h_1}\left(\frac{h_2}{h}, \mathrm{R}_e, \mathrm{C}_P, \theta\right) \quad (3)$$

Where:

(u_0) is inlet flow velocity, (h_1) is the height of inlet section, (h_2) is the height of outlet section, (ρ_w) is specific mass of fluid, (μ) is dynamic viscosity, $E_R = \frac{h_2}{h}$ is expansion ratio, ΔP is pressure changes, (θ) is angle step and (R_e) is Reynolds number.

C. Mathematical model

In this study, by attention to verifying numerical model, turbulence model has been used to simulate circulation flow over backward facing step. Thus, the governing equations are as following:

Continuous equation:

$$\frac{\partial P}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (4)$$

Momentum equation:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\left(\mu + \mu t\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \quad (5)$$

K- Equation:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial\left(\rho u_i k\right)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\frac{\mu + \mu t}{\sigma k}\right)\frac{\partial k}{\partial x_i}\right] + Gk - \rho\varepsilon \quad (6)$$

ε-Equation:

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial\left(\rho u_i \varepsilon\right)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\frac{\mu + \mu t}{\sigma\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{K}Gk - C^*_{2\varepsilon}\rho\frac{\varepsilon^2}{K} \quad (7)$$

In above equations: P is corrected pressure, u_i is velocity, ρ and μ are respectively the volume fraction average density and molecular viscous coefficient; μ_i is turbulent viscous coefficient that can be obtained by turbulent kinetic energy and turbulent dissipation rate, its expressed as Eq. (8):

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (8)$$

The Gk in Eq. (6) is turbulent kinetic energy item that induced by average velocity gradient that it can be represented as:

$$Gk = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial u_j} \quad (9)$$

$$C^*_{2\varepsilon} = C_{2\varepsilon} + \frac{c\mu\rho\eta^3\left(1 - \frac{\eta}{\eta_0}\right)}{1 + \beta\eta^3} \quad (10)$$

$$\eta = \frac{Sk}{\varepsilon},\ \mathrm{S}=\sqrt{2S_{ij}S_{ij}} \quad (11)$$

The constant values in governing equation are presented according to table 2.

TABLE 2. CONSTANT IN GOVERNING EQUATION

C U	$C_{2\varepsilon}$	$C_{2\varepsilon}$	σk	$\sigma\varepsilon$	η_0	β
0.0845	1.42	1.68	0.72	0.72	4.38	0.012

III. RESULTS AND DISCUSSION

In this study, the flow over back-ward facing step was simulated for investigation of the reattachment length by the experimental data of Eaton and Johnston (1980). The results of verification of numerical modeling indicated that turbulence model has the most agreement with experimental data. Fig. 4, shows the velocity distributions by using turbulence model for ER=3. Numerical modeling of flow over a backward-facing step is carried out for different conditions according to the table 3. After simulation of flow over step, secondary flow added to $\frac{1}{3}$ the height of step to explore the reattachment length according to Fig. 1

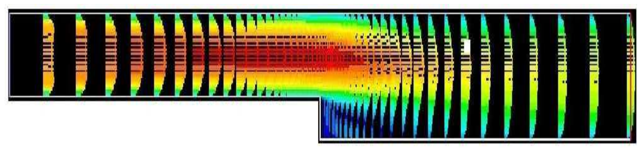
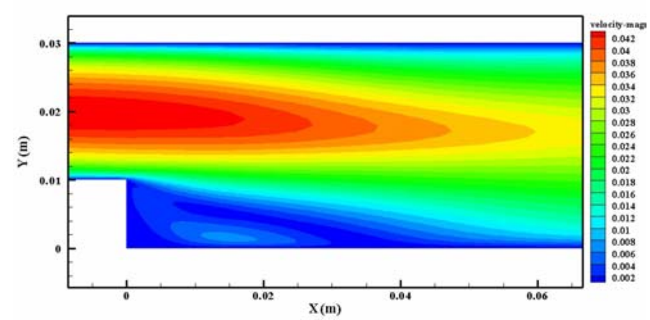


Fig 4. Velocity distribution – k - ε (RNG) model

TABLE3. CONFIGURATIONS USED IN PRESENT STUDY

E R	Re × 10 ^{3}	Step Angel
1.5, 2, 3, 4	20, 35, 55, 75	15, 30, 45, 90

According to Fig.5, the flow changes its path with changing sudden pressure and passing over step, and the flow is separated of upper edge of step. The separated flow creates a recirculation flow zone at the downstream step.



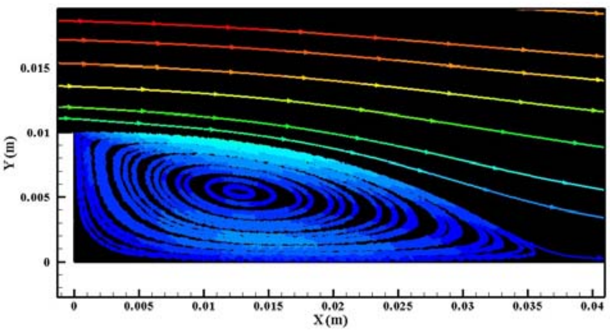


Fig.5. Velocity and streamline contours of recirculation zone of backward facing step in ER=3

In Fig. 6, the changing the reattachment length has been illustrated for different expansion ratio of step. Fig. 6, shows the rates of reattachment length $\left(\frac{x_r}{h}\right)$ in four different ratios versus step angel. According to this fig, it can be inferred that as the step angle increases, the reattachment length increases until 45° and it remains almost constant thereafter. Also in constant step angel, when expansion ratio is increased from 1.5 to 4, the reattachment length increases.

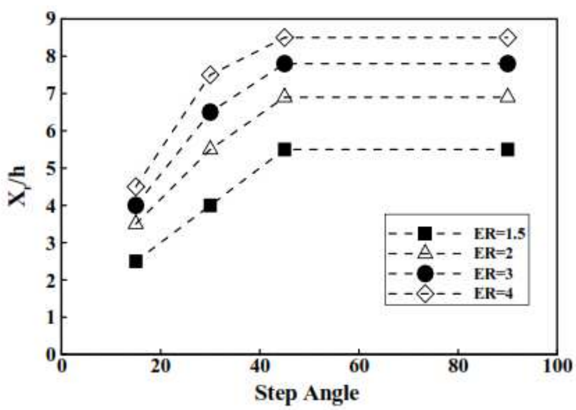


Fig6. Variation of reattachment length versus step angel- ER=3

Fig. 7 shows the variation of X_r versus Reynolds number for ER=3 and different step angels. This fig illustrated that with increasing Reynolds number, the reattachment length increases and in constant Reynolds number, it increases with increase step angels.

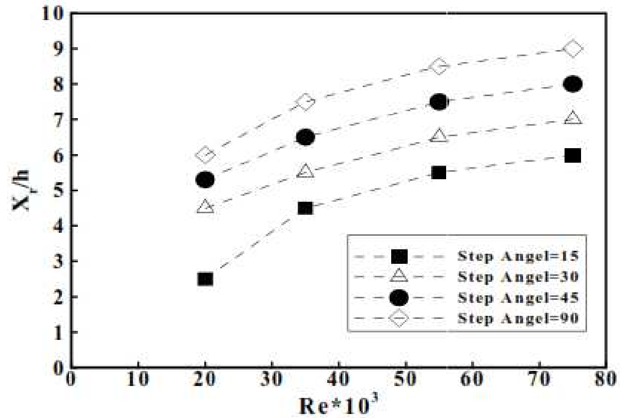


Fig 7. Variation of reattachment length versus Reynolds number - ER=3

Because of the cavitation dangers in stepped channels, pressure distribution at the downstream of step is important. In this study, pressure contours has been drawn by using turbulence model as following Fig.8. By reason of separation flow and eddies of this zone, P_{min} and P_{max} occurs respectively in in vertical wall and horizontal level of step.

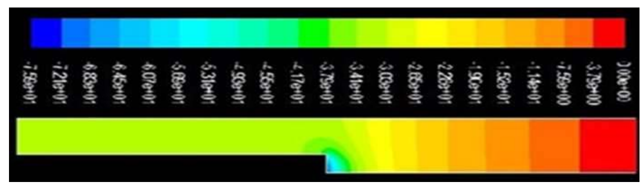


Fig 8. Pressure contours over step

In Fig. 9, numerical values of pressure coefficient along the bottom wall were compared to experimental data obtained Eaton and Johnston(C_P is defined as $C_P = \left(2\left(P - P_r\right)/\rho U_r^2\right)$ where, P_r and U_r are the pressure and velocity, on the centerline at the inlet). The numerical values of pressure coefficient have good agreement to experimental data. Also, it can be seen the reattachment length increases with increasing pressure coefficient.

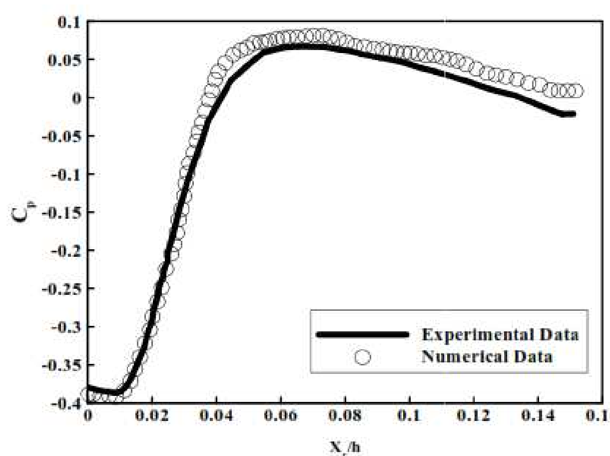


Fig 9. Comparison of Pressure coefficient along the bottom wall

After the exploration of the reattachment length of flow over backward facing step, the secondary flow added to the height of step then the effect of it investigated on recirculation zone of flow. As it can be seen in Fig.10, the flow mechanisms changes with adding flow to the height of step. In this case, eddies traps in the down of edge step between initial flow and secondary flow, and the length of flow recirculation zone reduces. In Fig. 10, the length of recirculation flow zone has been presented versus step angel for different Reynolds number.

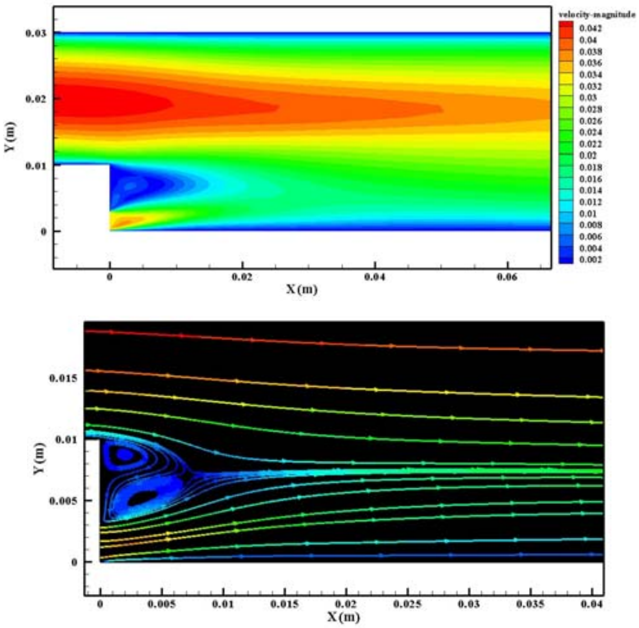


Fig 10. Velocity and streamline contours of recirculation zone of backward facing step in the height of step ER=3

Based on this Fig. 11, it can be concluded that the length of recirculation flow zone reduce with increasing step angel. Also, increasing Reynolds number caused to decreases length of recirculation flow zone for constant step angel. The length of recirculation flow zone decreases until 45° and it remains almost constant thereafter.

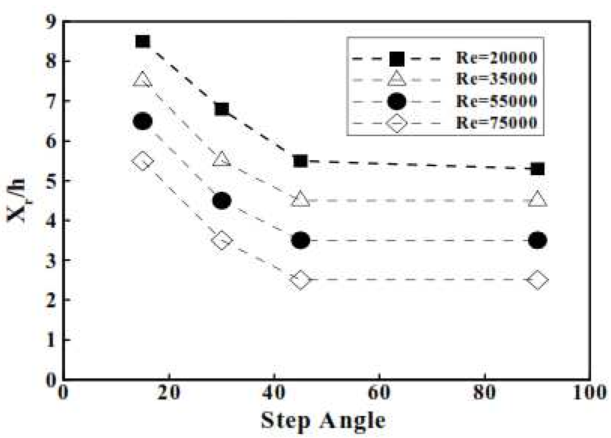


Fig 11. Recirculation flow zone with secondary flow – ER=3

IV. CONCLUSION

In this study, the relation of the reattachment length and Reynolds number, step angel and expansion ratio are explored by using Computational Fluid dynamic. For this purpose, the experimental results of Eaton and Johnston are used to verifying numerical model. The results showed that k- ε *(RNG)* turbulent model is the most suitable model to simulate the reattachment length. The results analysis indicates that with increasing step angle, expansion ratio and Reynolds number increase the length of recirculation flow zone. Also with increasing Reynolds number when secondary flow is added to $\frac{1}{3}$ height of step, the diameter eddy and the length of recirculation flow zone decrease. Moreover, increasing the coefficient of pressure increases the length of recirculation flow zone.

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