

Simulation Investigation of Flows over an Inclined Backward-Facing Step

¹*Casimir Uchenna Agbakaja, ²Berkah Fajar Tamtomo Kiono, ³Khoiri Rozi

^{1,2,3}Department of Mechanical Engineering, Diponegoro University, Jl. Prof. Sudharto, SH, Semarang 50275, Indonesia

*Corresponding Author's E-mail: uchenna.agbakaja@st.futminna.edu.ng; casimiruchennaagbaka@undip.students.ac.id

Abstract - This study deals with the flow investigation of a backward-facing incline step using the RANS turbulence model ($STD k - \epsilon$ and $SST k - \omega$) with angle $5^\circ, 10^\circ$ and 15° . The Reynolds number used are 17,500 and 30,000. The motivation for this research stems from the fact that in aerodynamics analysing, the flow over an inclined step will enable us in understanding the features of the rear wake. A great amount of the energy necessary to propel the airfoil gets dissipated by vortex shedding generated in the rear, so it is of paramount importance to understand the properties of the wake. In this paper, the flow over a backward step is analysed and the results are compared with existing scholarly literature for validation. Attention was paid specifically to the separation region behind the step and the shear layer relaxation after the reattachment in the downstream part of the channel. The influence of Reynolds number, expansion ratio and turbulence intensity on flow separation and reattachment was investigated and obtained for various step angles using the $STD k - \epsilon$ and $SST k - \omega$ model and it was observed that the $SST k - \omega$ predict recirculation better than the $STD k - \epsilon$ model with about 0.1 percent. In conclusion, the upstream boundary layer plays a decisive role in flow separation and reattachment.

Keywords: Backward-facing step flow, vortex shedding, recirculation, reattachment length.

I. INTRODUCTION

Boundary layer theory discovery by Ludwig Prandtl in the twentieth century laid the foundation for the extensive study on separated flows [1]. Flow separation and reattachment influence the mechanism of heat transfer and fluid flow. The backward-facing step became a benchmark model for the study of flow reattachment and separation as a result of its importance in engineering applications. The usefulness of such flows to engineering applications has been dutifully emphasized in many scholarly publications [2, 3, 3]. Industrial heat exchangers, combustors, turbo machinery, cooling of nuclear reactors, etc. are examples where the flow goes over a step experiences sudden expansion. A lot of

research has been dedicated to this field using numerical methods [4, 5] and experimental method by [6].

Curious efforts have been made to develop sophisticated theoretical techniques and experimental methods to examine flows with separation regions. However, as a result of the complexity with flow separation and reattachment, the experimental and numerical methods capable of accurately studying these flow characteristics are still not near perfect [7]. For the purpose of better understanding, either experimentally or numerically of the fluid flow following separation and reattachment, the two-dimensional flow past a backward-facing step has proven to be a building-block flow as well as a standard test problem those developing turbulence models, and it has been addressed by numerous scholars and authors adopting so many experimental and numerical approaches [2, 3, 8, 6, 7, 9, 10].

In the flow past a backward-facing step, the oncoming boundary layer detaches from the surface and a region of recirculation is created downstream of the step. The separated shear layer grows rapidly and further downstream of the step, it reattaches to the channel. The behaviour of this separated layer, its growth and turbulence properties, are of paramount importance in various engineering applications. Notwithstanding the level of attention backward-facing step flow has gained because of due to its usefulness, the downstream flow confined in a channel has not been fully understood. This is somewhat because of the complex nature of the shear layer turbulence [11] which is influenced by the highly turbulent region of recirculation and the strong adverse pressure gradient.

Some of the foremost studies of sudden expansion flows were limited to flow visualizations [2] and measurements for wall heat transfer [12, 13, 14]. Their works provided details on almost the entire structure of the sudden expansion flow. They showed a very complex turbulent structure in the case of large Reynolds number flows displayed by the heat transfer patterns near the wall. [11, 15, 16, 17] and many others, tried to study the flow structure behind a plane backward-facing step by using hot wire anemometer. Since this method have the limitation of resolving flow direction, measurements were

limited to the regions with no flow reversals expected. The experiments of Bradshaw and Wong [11] were conducted in a large wind tunnel, without the confinement of the step flow by a top wall. Though, their study indicated a flow redevelopment largely influenced by the structure of the flow upstream of reattachment, reaffirming the importance of initial separated shear layer on the entire flow.

The flow downstream of reattachment is affected by the structure of the flow at reattachment since the zone forms the conditions for the subsequent development of flow. Abbot and Kline [2] noted that, even though modern calculation techniques predict boundary layers and free shear layers quite well, the length of reattachment for the backward-facing step is predicted below per by 20% and the flow field predictions becomes more critical as the flow goes into the region of recovery. They posited that more basic physical understanding of the free shear layer interaction and a wall is necessary to improve computational techniques and physical.[18] experimentally, the unstable heat transfer in the downstream of laminar flow over a 2D backward-facing step. Their study showed that the flow pulsation had effects on heat transfer depending on the geometry under study. Khanafer et al [19] gave a report on the heat transfer of laminar mixed convection flow on a backward-facing step under the conditions pulsating. The results further proved that Reynolds number greatly affects heat transfer characteristics and fluid flow.

This paper therefore aims to examines and make comparison on the CFD simulation of fluid flow over a wall inclined backward-facing step in a 2D geometry with Standard $k - \epsilon$ and the SST $k - \omega$ turbulence model by analysing the effect of expansion ratio, step angle and step height on recirculation zone and reattachment length. The paper focuses on the mean separation bubble structure over the backward-facing step at large Reynolds number ($R_e = 17,500 - 30,000$). With this Reynold's numbers, I present, in this paper, a systematic CFD examination of the effect of expansion ratio, incline angle, turbulence intensity and step height on recirculation zone and reattachment length. Interest is placed on visualizing the velocity magnitude, pressure distribution, dissipation rate and turbulent kinetic energy of the flow. The results can be used as a reference and be applied in future research involving flows in backward- facing step.

1.1 Objective

This research aims are as follows:

- To study and make the comparison between the Standard $k-\epsilon$ and SST $k-\omega$ turbulence model on a backward facing inclined step geometry.

- To calculate flow separation and recirculation zone at different Reynolds numbers.
- To ascertain the effect of step height, step angle, expansion ratio, turbulent intensity and Reynolds number on recirculation and reattachment.
- To visualize streamlines, velocity magnitude, pressure distribution coefficient, turbulent kinetic energy, and turbulent dissipation rate on the flow field.

II. METHODOLOGY

Turbulence modelling has been frequently underlined in aeronautical applications as one of the major obstacles towards accurate and efficient flow predictions [20]. It will remain in the foreseeable future, an important matter in research aiming at improving CFD accuracy and robustness.

2.1 Reynolds-averaged Navier-Stoke Equation

The Reynolds-averaged Navier-Stokes equation (RANS) is time-averaged equations of fluid flow. RANS equations are basically used to describe turbulent flows.

$$\rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \rho \bar{f}_i + \frac{\partial}{\partial x_j} \left[-p \delta_{ij} + \mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho u'_i u'_j \right]$$

The left-hand side of this equation represents the change in the mean momentum of a fluid element owing as a result of unsteadiness in the mean flow and the convection by the mean flow. This change is balanced by the mean body force and the isotropic stress owing to the mean pressure field, the viscous stresses, and apparent stress ($-\rho u'_i u'_j$) owing to the fluctuating velocity field, generally referred to as the Reynolds stress. This nonlinear Reynolds stress term requires additional modelling to close the RANS equation for solving and has led to the creation of many different turbulence models.

2.2 Derivation of the RANS equation

The basic tool required for the derivation of the RANS equations from the instantaneous Navier-Stokes equation is the Reynolds decomposition. Reynolds decomposition refers to separation of the flow variable (like velocity (u) into the mean time-averaged component (\bar{u}) and the fluctuating component (u'). Because the mean operator is a Reynolds operator, it has a set of properties. One of these properties is that the mean of the fluctuating quantity is equal to zero ($u' = 0$). Thus,

$$u(x, t) = \bar{u}(x) + u'(x, t)$$

Where $x = (x, y, z)$ is the position vector.

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} + u'_j \frac{\partial u'_i}{\partial x_j} = \bar{f}_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j}$$

The momentum equation can also be written as,

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \bar{f}_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial u'_i u'_j}{\partial x_j}$$

On further manipulation, these yields,

$$\rho \frac{\partial \bar{u}_i}{\partial t} + \rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \rho \bar{f}_i + \frac{\partial}{\partial x_j} [-p \delta_{ij} + 2\mu \dot{S}_{ij} - \rho u'_i u'_j]$$

Where, $\dot{S}_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$ is the mean rate of strain tensor.

Finally, since integration in time removes the time dependence of the resultant terms, the time derivative must be eliminated, leaving:

$$\rho u_j \frac{\partial u_i}{\partial x_j} = \rho \bar{f}_i + \frac{\partial}{\partial x_j} [-p \delta_{ij} + 2\mu \dot{S}_{ij} - \rho u'_i u'_j]$$

2.3 Equation of Reynolds stress

The time evaluation equation of Reynolds stress is given by:

$$\begin{aligned} \frac{\partial u'_i u'_j}{\partial t} + u_k \frac{\partial u'_i u'_j}{\partial x_k} &= -u'_i u'_k \frac{\partial u_j}{\partial x_k} - u'_j u'_k \frac{\partial u_i}{\partial x_k} \\ &+ \frac{p'}{\rho} \left(\frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i} \right) \\ &- \frac{\partial}{\partial x_k} \left(u'_i u'_j u'_k + \frac{p' u_i}{\rho} \delta_{jk} - \frac{p' u'_j}{\rho} \delta_{ik} \right. \\ &\left. - \nu \frac{\partial u'_i u'_j}{\partial x_k} \right) - 2\nu \frac{\partial u_i}{\partial x_k} \frac{\partial u'_j}{\partial x_k} \end{aligned}$$

This equation is very complicated. If $u'_i u'_j$ is traced, turbulence kinetic energy is obtained. The last term $\nu \frac{\partial u_i}{\partial x_k} \frac{\partial u'_j}{\partial x_k}$ is turbulent dissipation rate. All RANS models are based on the above.

2.4 Model Coefficients

The model coefficients for the standard $k - \epsilon$ model have evolved through time.

Table 1: Model coefficients

Model	σ_k	σ_ϵ	$C_{1\epsilon}$	$C_{2\epsilon}$	C_p
Jones & Launder (1972)	1.0	1.3	1.55	2.0	0.09
Launder & Spalding (1974)	1.0	1.3	1.44	1.92	0.09
Launder & Sharma (1974)	1.0	1.3	1.44	1.92	0.09

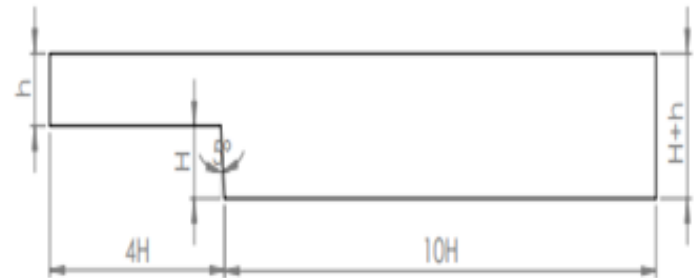
The Launder & Sharma (1974) coefficients are the most up to date.

2.5 Geometry

The geometry consists of a BFS model as shown below. The Reynolds numbers are 17,500 and 30,000 while the angle of variation ranges from $5^\circ, 10^\circ$, and 15° degrees respectively. The fluid flow simulation will be applied to all the parameters. From the Reynolds number, as in the equation, the fluid inlet velocity value will be obtained as input for the processing. The geometry of the BFS model used in this study is shown in figure 3.2 and the dimensions specification of the BFS model are listed in table 2.

2.6 Inclined Backward Facing Step Model

Variation: $5^\circ, 10^\circ, 15^\circ$.



$ER = 2; 2.2; 2.4.$

$Re = 17,500; 30,000.$

Figure 1: 2D Geometry for backward facing step flow with inclination angle of 5°

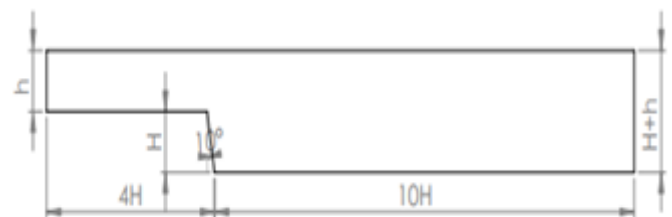


Figure 2: 2D Geometry for backward facing step flow with inclination angle of 10°

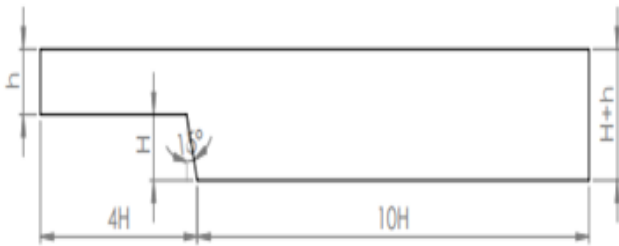


Figure 3: 2D Geometry for backward facing step flow with inclination angle of 15°

Table 2: Specification of the sizes for backward facing step

Geometry features	Dimension (H =50mm, 60mm, 70mm & h=50mm)
Step height	H
Upstream height/inlet height	H
Downstream height	H+h
Length	14H
Inclination angles	$5^\circ, 10^\circ, 15^\circ$

Table 3: Configuration used in present study

ER	R_e	Step angle
2, 2.2, 2.4	17,500; 30,000	$5^\circ, 10^\circ, 15^\circ$

Mesh refinement study

To obtain a grid independent solution, a grid refinement test was performed.

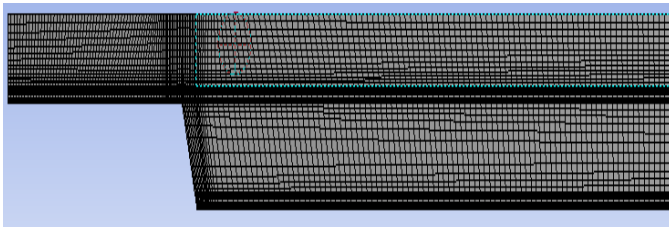


Figure 4: Mesh

A CFD solution can never be trusted unless it is checked whether the result depends on the grid or not. The output of a coarser mesh or finer mesh is never the same. A coarse mesh may be quick but unable to capture the flow characteristic; a fine mesh may be accurate but requires high computational resources. A stable and accurate mesh relies in having quality elements. So, to what extent we need to vary the mesh to get the accepted level of tolerance can be found from grid independence test.

The table and Figure 8 describe the result as satisfactory for the grid refinements. In this problem 6604 elements are used for the whole domain. Using more elements are time consuming and do not improve the result significantly.

Table 4: Mesh independence: No of cells versus velocity

No of elements	Velocity	Max Velocity	Notation
6005	7.12	7.15	A
6008	7.18	7.20	B
6012	7.23	7.24	C
6034	7.46	7.51	D
6604	7.46	7.62	E
6690	7.46	7.86	F
7034	7.46	7.88	G

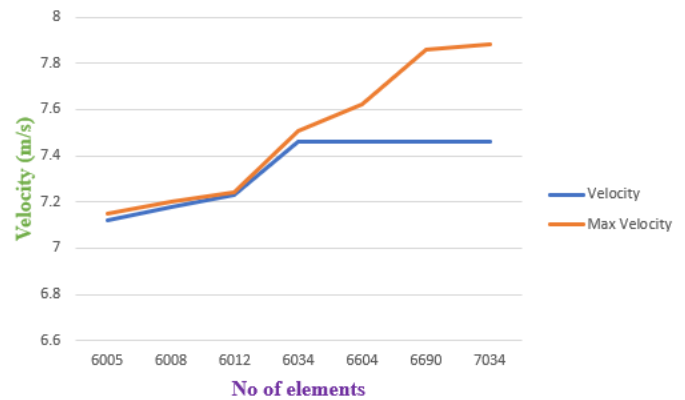


Figure 5: Mesh independence graph

The grid independence for one geometry will be applicable only for that geometry. Grid independence means calculation results change so little along with a denser or looser grid that the truncation error can be ignored in numerical simulation.

Based on Table 2, mesh D to G show constant velocity but so much variation in the maximum velocities was noticed from A to E until F where the difference in grid size shows little difference. Based on this, the F grid was chosen for the research of the test object because the number of cells owned by mesh F is less than mesh G so it can speed up processing time when running fluent software. The results of the grid test are then graphed as shown in figure 5.

Turbulence Model

The models used in this research are the standard $k - \epsilon$ and $SST k - \omega$ turbulence model respectively. The $k - \epsilon$ model is useful for free-shear layer as well as confined flows where the Reynolds shear stress are more important, while the $SST k - \omega$ model proposed by Menter in 1994 gives better agreement with experiments and with mildly separated flows due to the viscosity limiter. Hence it is best for external aerodynamics or simulation where separation is important.

Materials

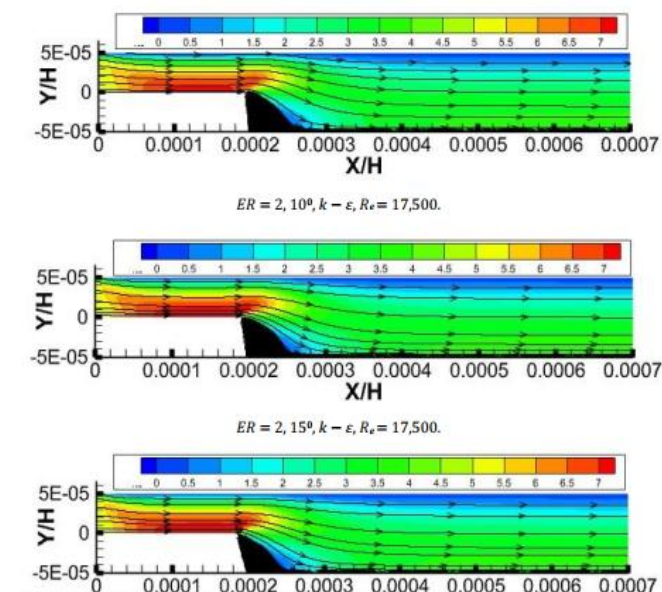
The fluid used in this study is air with density (ρ) = 1.225 kg/m^3 and dynamic viscosity (μ) = $1.7894 \times 10^{-5} \text{ kg/ms}$.

Air was modelled as an incompressible fluid, and it was also assumed that the kinematic and thermodynamic properties are constant. So, no change was required in the materials panel.

III. RESULTS AND DISCUSSION

3.1 Relationship between recirculation and wall inclination angle

In this study, the fluid velocity decreases after the step and this is caused due to the sudden expansion. The decrease in velocity with increases in area proves that the flow is respecting the law of conservation of momentum. From the velocity contours, it is also clear free shear layers originated due to higher velocity on the top of the fluid in comparison to momentum in the wake of the step. The flow physics of recirculation of the fluid around the step is caused due to continues retardation of the flow, thereby causing the flow to reverse and is driven by the presence of higher velocity vortices in the separated shear layer which is also rightly mapped as shown in the velocity vector plots. Lastly, a reattachment of the separated flow is shown by the velocity contour downstream of the step proving that the simulation correctly correlates with the flow physics.



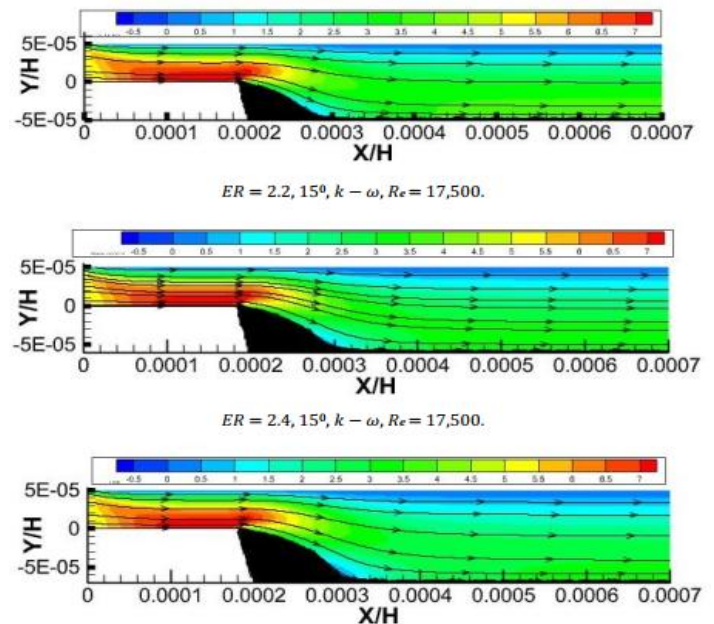
Result obtained from the simulation shows that the length of recirculation decreases with an increase in inclined upper wall angle. This agrees with the work of J. Rajasekaran [1] and [22]. This is also in acceptance with the experimental work

of [23] that for constant Reynolds numbers an increase in inclination angle reduces the length of reattachment.

[24] Also studied the turbulent forced convection of flow progression in a rectangular duct where an inclined forward step was located. Flow was regarded as turbulent, and they used the $k - \epsilon$ turbulence model to solve Navier-Stokes equations. They concluded by saying that the step length and inclination angle played a decisive role in the fluid hydrodynamic behavior.

3.2 Effect of expansion ratio (ER) on reattachment

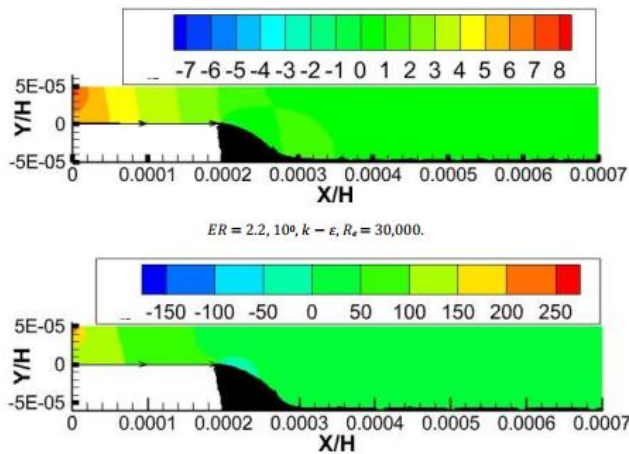
From this research, it was observed that recirculation increases with an increase in expansion ratio. This agrees with the work of Eaton and Johnston [6, 8, 25, 26, 27]. According to [27], as the expansion ratio is increased, the effect of Reynolds number also increases on reattachment length. Thus, for low expansion ratios, the reattachment length is independent of Reynolds number and for any expansion ratio, reattachment length initially increases. This is possible because at low Reynolds number and high expansion ratio, the flow gets enough space and time to reattach to the boundary, thereby reducing the reattachment length. But in case of high Reynolds number, the reverse phenomena happen, i.e., the value of reattachment increases with an increase of expansion ratio.



It should be mentioned here that [28] stated that the mean bubble structure is independent of expansion ratio at constant Reynolds number. This is slightly supported by the experimental work of [30] which shows that in the existence of high Reynolds number regime, the recirculation region is nearly identical for all expansion ratios.

3.3 Relationship between pressure coefficient (Cp) and reattachment length.

The relationship between pressure coefficient (Cp) and reattachment length was evaluated in this simulation and it was concluded that the reattachment length increased as the pressure coefficient increases. This agrees with the experimental work carried out by [8] and the numerical results obtained by [25].



3.4 Effect of wall inclination angle on pressure

This research showed that as the angle of inclination increases, the pressure acting on the upstream surface decreases, thereby causing the lift on the body to increase. This agrees well with the numerical investigation of [31]. The variation of pressure on the inclined surface endures a minor increase with the increase in the Reynolds number.

This pressure fluctuation could be due to the sudden change in geometry at the corner, leading to variations in the velocity of the flow. An important phenomenon to be observed from both figures is that the pressure decreases gradually from the upstream but there was a major decrease on the wall inclined surface and the step. The increase was more for the 10° inclined surface. This behaviour according to [31] is attributed to the velocity profile development on the respective surfaces. The increase in the wall inclination angle brings about an increase in the step length and this have a minimal effect on the pressure distribution over the inclined surface as the pressure tends to decrease marginally.

3.5 Effect of Reynolds number and expansion ratio on turbulent kinetic energy

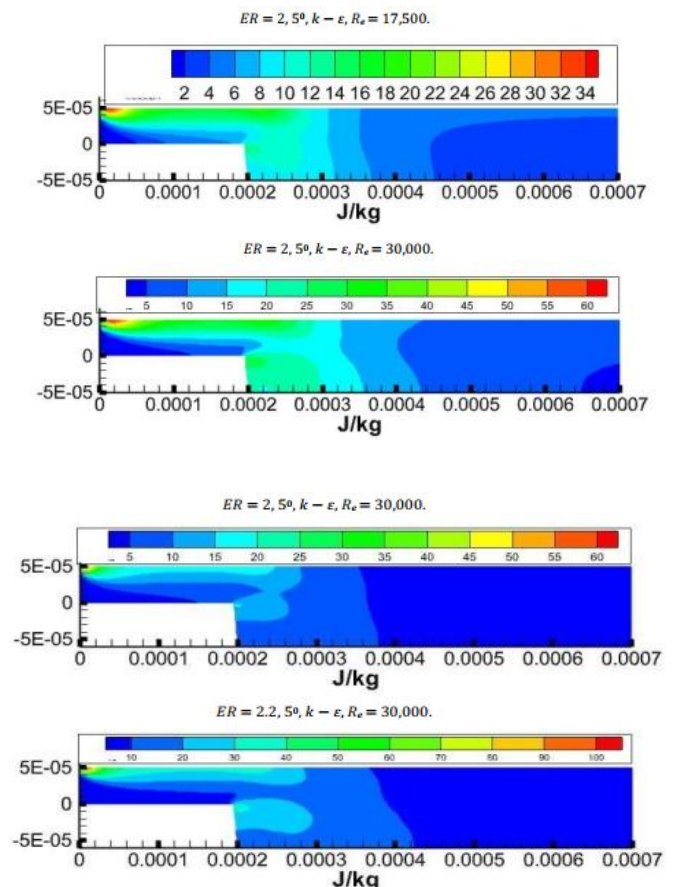
A vortex system occurs when a wall turbulent boundary layer encounters a bluff body. This causes the turbulent boundary layer to separate from the wall under adverse pressure gradient and reorganize into coherent vortices. The

turbulent kinetic energy in this research was found to increase with Reynolds number and expansion ratio.

This is primarily due to an increase in fluctuating velocity in the x-direction near the wall. High turbulent kinetic energy near the wall was also observed at high Reynolds number by [32] and by [33]. In this paper, the expansion ratio was found to have a particular strong influence in the development of the turbulent kinetic energy in the separated shear layer. Larger step height leads to higher turbulence and faster growth of the unstable shear layer. As a result of this, larger recirculation lengths occurred with larger expansion ratios.

This agrees well with the experimental work of [34] on the effect of Reynolds number on turbulent junction flow fluid dynamics and heat transfer.

They studied a wide range of approach momentum thickness Reynolds numbers and although the time-mean flow field does not show significant Reynolds number dependency, the normalized turbulent kinetic energy in and around the vortex core increases with Reynolds number, and the high heat transfer associated with the junction flow moves closer to the junction. These effects they believe are linked to the increasing randomness in the position of the primary junction flow vortex as the Reynolds number increases.

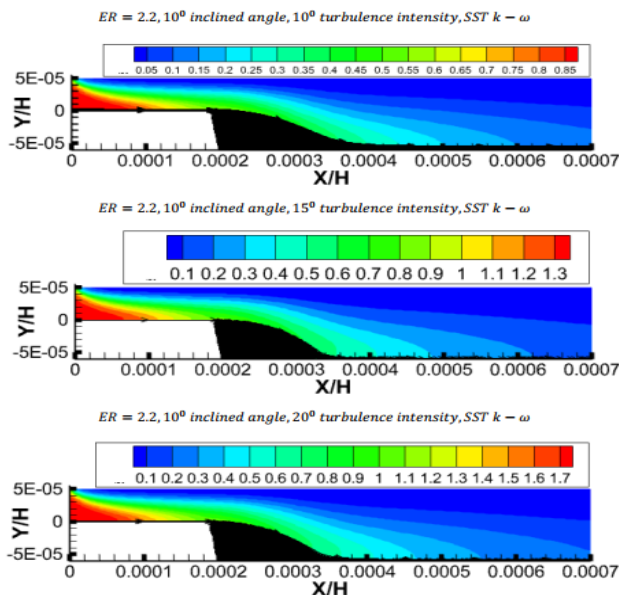


3.6 Comparison of reattachment length with turbulence intensity

It was observed in this study that as the turbulence level in the free stream region upstream of the step became higher, the reattachment length became shorter.

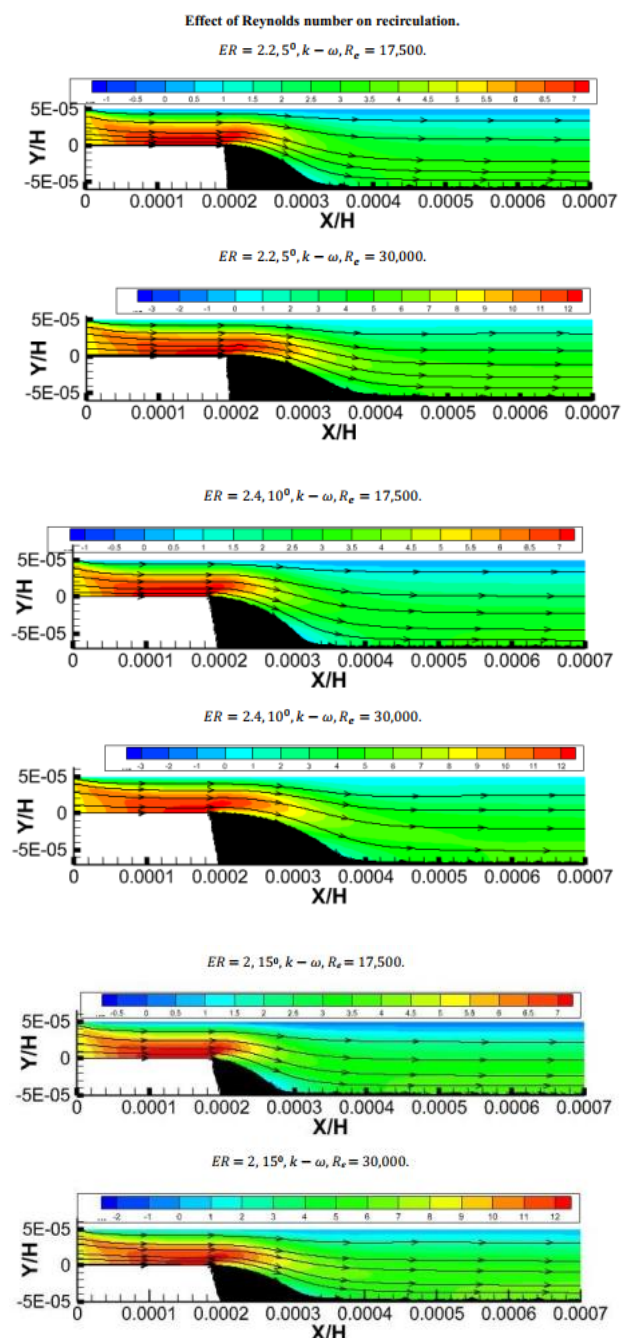
It was also observed that larger expansion ratios lead to higher turbulence intensities inside the separated shear layer. This agrees with the experimental work of [35]. The increase in turbulence intensity is more pronounced at the initial stage of the separated shear layer, immediately downstream of the step. The increase in turbulent diffusion leads to a faster shear layer growth and velocity development before the flow reattaches. As a consequence of this, smaller normalized mean reattachment lengths are obtained for larger expansion ratios. This is also in conformity with the result of [17]. They isolated and systematically studied the effects of upstream boundary layer and free stream turbulence on reattachment. Their results indicated that higher upstream turbulence levels lead to reduced reattachment lengths. In another study, [36] found that increased boundary layer thickness at step results in lower reattachment pressure gradients and reduced shear layer turbulence intensities. The reattachment zone is reduced by the turbulence. One explanation for this phenomenon is that the turbulence in the approach boundary layer promotes spatial fluctuation of the separated shear layers and induces an earlier reattachment.

[37] Stated that for higher Reynolds numbers, the reattachment length dependency disappears but the expansion ratio becomes relevant in the determination of the reattachment length. They compared previous experimental data in a similar configuration to their present results to clarify the flow dependency on external parameters, e.g., expansion ratio and Reynold number and it was found that that there is no constant trend after $R_e > 105$ but a decrease in the recirculation length, meaning that the reattachment point depends on other parameters. It is possible to highlight that, for high Reynolds numbers, the expanding ratio dependency becomes relevant in the determination of the recirculation length.



3.7 Effect of Reynolds number on reattachment.

From this simulation, it was observed downstream static recirculating vortex length tends increase with the increase of Reynolds number. Reynolds number of 17500 and 30000 was used. The result obtained is in conformity with the numerical computation carried out by [26].



[30] Studied the effect of Reynolds number on mean reattachment length for ER from 1.1 – 2.0. The Reynolds number range covered in the experiments was from about 6,000 – 67,000. The reattachment length was seen to increase at lower Reynolds number till around 20,000, above which it saturates and becomes nearly independent of Reynolds number. This behaviour is in accordance with that observed in the literature, for example by [8, 28, 36].

[31] Agreed based on quantitative observations made from their simulations and it was evident that at $R_e = 500$, the vortex dissipation is more organized, but the simulations at $R_e = 800$ showed much faster and disorganized vortex dissipation. This is because as Reynolds number increases, the kinetic energy associated to each fluid particle also increases and momentum interchange between particles increases, producing a quicker and higher disorganized vortex dissipation. This fact emphasizes the global nature of flow dynamics. They further contented that a detailed three-dimensional calculation was necessary to explore the three-dimensional nature of the flow at moderate Reynolds and to determine the exact Reynolds number for the flow transition from two-dimensions to three-dimensions.

3.8 Comparison of turbulence model ($STD k - \epsilon$ & $SST k - \omega$)

From this study, it was observed that the reattachment length more for the $SST k - \omega$ model compared to the $STD k - \epsilon$ model. [15] Suggests that standard $k - \epsilon$ model failed to predict correct reattachment lengths on a flow over a 2D backward-facing step flow. This they thought could be due to its insensitivity towards positive pressure gradients which yields poor performance especially when the flow experiences strong separation and large pressure gradient. One equation models such Spalart-Allmaras also failed to predict the correct reattachment length as this could be due to its inability to model internally separated and free shear flow [16].

The Shear stress transport (SST) model was found to be over predictive of the reattachment zone. [15] Performed comparison between different turbulent model along with the relevant wall treatment with the Driver and Seegmiller experiment of Backward facing step (BFS), 1985 which suggested that The RNG $k - \epsilon$ model provided the best option as it computed a closer value to the actual experiment. However, in this simulation, the $SST k - \omega$ turbulent model was selected due to its ability to calculate flow properties in the free-stream turbulent flow region distant from the wall.

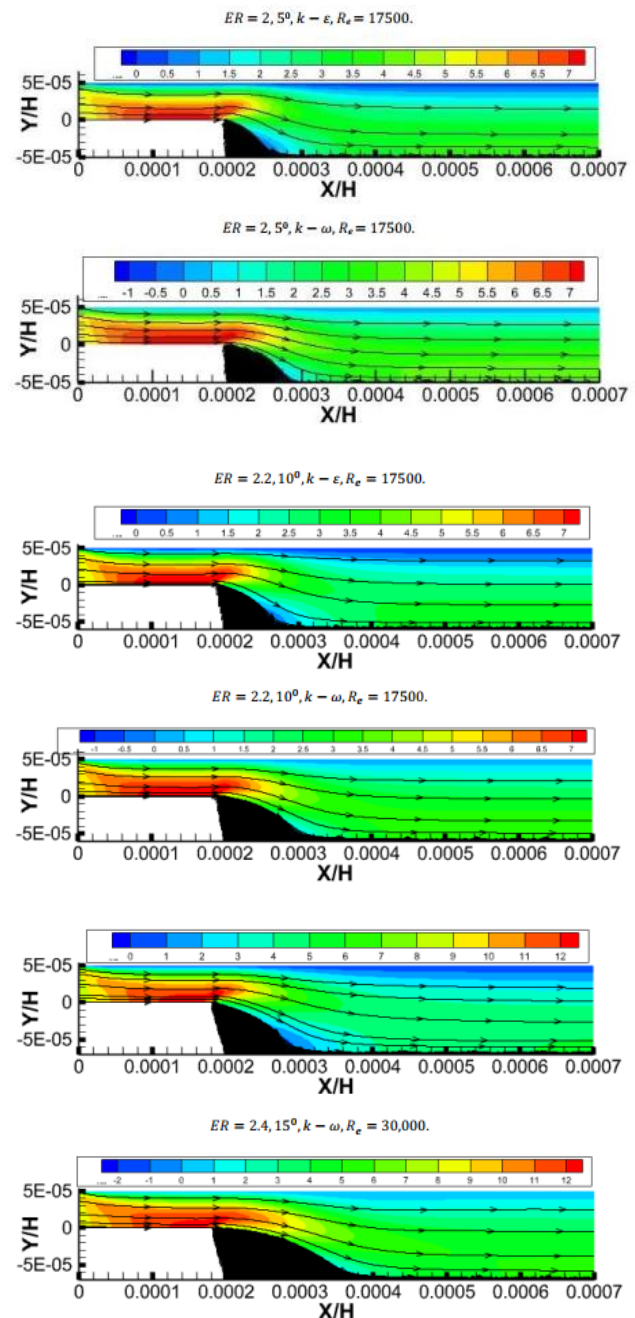
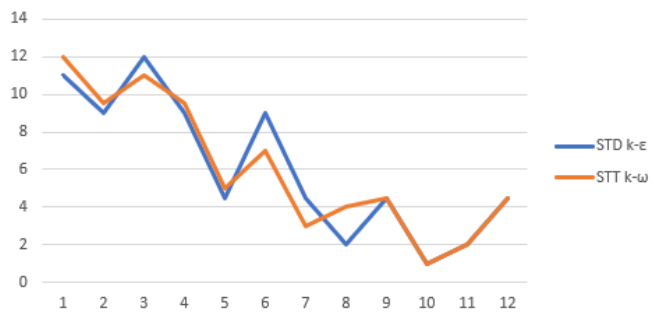


Table 5: Comparison of Reattachment Length from the $k - \epsilon$ and $k - \omega$ Turbulence Model

ER	R_e	$SST k - \omega$ (X/H)	$STD k - \epsilon$ (X/H)	R_x	R_y	$R_x - R_y = D$	D^2
2.0	17,500	2.8	2.5	11	12	-1	1.00
2.2	17,500	2.9	3.2	9	9.5	-0.5	0.25
2.0	17,500	2.4	3.0	12	11	-1	1.00
2.2	17,500	2.9	3.2	9	9.5	-0.5	0.25
2.4	17,500	4	4.8	4.5	5	-0.5	0.25
2.0	30,000	2.9	3.6	9	7	2	4.00
2.2	30,000	4	5.2	4.5	3	1.5	2.25
2.0	30,000	5	4.9	2	4	2	4.00
2.2	30,000	4	5.8	4.5	4.5	0	0.00
2.4	30,000	5.6	6.0	1	1	0	0.00
2.0	30,000	3	3.4	2	2	0	0.00
2.4	30,000	4	4.2	4.5	4.5	0	0.00

COMPARISON OF REATTACHMENT LENGTH FROM THE STD K-ε AND SST K-ω TURBULENCE MODEL



$$r_k = 1 - \frac{6\sum D^2}{N(N^2 - 1)}$$

$$r_k = 1 - \frac{6 \times 13}{12(126^2 - 1)} = 1 - \frac{78}{190500}$$

$$= 1 - 0.0004$$

$$= 0.99$$

$$= 99.9\%$$

From the above, a correlation of 99.9% was obtained between the $k - \epsilon$ and $k - \omega$ turbulence model.

IV. CONCLUSION

The results provide additional evidence that initial conditions such as boundary layer thickness, Reynolds number and pressure gradient/expansion ratio have significant impact higher order turbulence statistics and on the mean flow properties. These observations further reinforce the importance of the upstream conditions to accurate predictions of reattachment and turbulence statistics.

The effects of Reynolds number (17,500 and 30,000), expansion ratio (2, 2.2, 2.4), pressure coefficient, and turbulence intensity and turbulent kinetic were examined, and the following results were obtained:

- **Reynolds number:** It was evident that the vortex shedding was more organized at low Reynold number. This is believed to be due to lower kinetic energy associated to each fluid particle and a subsequent decrease in momentum interchange.
- **Wall inclination angle:** The CFD results of the reattachment length decrease with an increase in inclined angle and shows good agreement with the observations of [1, 23].
- **Turbulent kinetic energy:** The maximum turbulent kinetic energy was found at the upstream side of the wall. The turbulent kinetic energy was seen to increase with Reynolds number and expansion ratio. Larger step

height leads to higher turbulence and faster growth of the unstable shear layer.

Further study of the flow field suggests that the large range of scales in the flow is drawn under the primary vortex. These effects tend to destabilize the vortex and result in high turbulent kinetic energy.

- **Turbulent intensity:** As the turbulent intensity becomes higher, the reattachment length becomes shorter. This is consistent with the results of [17].
- **Pressure coefficient:** It was found that reattachment length increases with increasing pressure coefficient. This agrees well with the result of [26].
- **Pressure:** The increase in the wall inclination angle brings about an increase in the step length and this have a minor effect on the pressure distribution over the inclined surface as the pressure tends to decrease marginally.
- **Expansion ratio (ER):** From this research, it was indicative that recirculation length increased with an increase in expansion ratio. Larger expansion ratios lead to higher turbulence intensities. The increase in turbulent diffusion leads to a faster shear layer growth and velocity development before the flow reattaches. As a consequence of this, smaller normalized mean reattachment lengths are obtained for larger expansion ratios.
- **Turbulence model $STD k - \epsilon$ & $SST k - \omega$:** The $SST k - \omega$ model provides a better prediction of flow separation better than the $k - \epsilon$ and also accounts for its good behaviour in adverse pressure gradients. It also has the ability to account for the transport of the principal shear stress in adverse pressure gradient.

ACKNOWLEDGEMENT

The financial support of this work and the full funded scholarship award from Diponegoro University for undertaking the program of master in mechanical engineering is fully acknowledged.

To the many men and women in Nigeria and the world at large who are still tenaciously standing tall by upholding the ethos of moral uprightness and human dignity even in the face of threats and intimidation.

And lastly, I dedicate this work to the Dynastic Mech family and the Obidient movement in Nigeria for their incredible resolve towards fighting for a better country where man can be what he is meant to be: free and truly independent.

Vox Populi, Vox Dei.

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Citation of this Article:

Casimir Uchenna Agbakaja, Berkah Fajar Tamtomo Kiono, Khoiri Rozi, "Simulation Investigation of Flows over an Inclined Backward-Facing Step" Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 7, Issue 7, pp 1-11, July 2023. Article DOI <https://doi.org/10.47001/IRJIET/2023.707001>
