STUDY OF TURBULENT FLOW DUE TO EXPANSION IN OPEN CHANNEL USING ANSYS FLUENT

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BY

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CANDIDATE'S DECLARATION

I do hereby certify that the work presented is the report entitled "Study of turbulent flow due to expansion in open channel using ANSYS fluent" in the partial fulfillment of the requirements for the award of the degree of "Master of Engineering" in hydraulics and water resource engineering submitted in the Department of Civil Engineering, Delhi Technological University, is an authentic record of our own work carried out from December 2015 to July 2016 under the supervision of S.Anbu Kumar (Assistant Professor), Department of Civil Engineering.

I have not submitted the matter embodied in the report for the award of any other degree or diploma.

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Date: July 2016 (2K14/HFE/03)

CERTIFICATE

This is to certify that above statement made by the candidate is correct to best of my knowledge.

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ABSTRACT

Expansions in channel enable us to provide transition from a narrow to a considerably wide – section, which is important in the design of many hydraulic structures. In the transition, there is tendency of flow to separate from its diverging side walls and form turbulent eddies. This happens if the angle of divergence exceeds the limiting threshold value. This phenomenon leads to undesirable energy losses and erosion to the walls of the channel and also on the downstream side of the channel. Earlier, Researchers have done work on the optimization of horizontal shape of the transition so as to avoid flow separation but no concrete conclusion was derived from it. This project study extends the earlier investigation by means of fitting a hump in the vertical to restrict flow separation. This study makes use of CFD modelling approach. This approach allows systematic exploration of the variation of number of parameter like Divergence angle, Crest Height of hump and Froude number of subcritical flow. Flow quantities studied in this project are velocity, Eddy structure and vorticity. These quantities are available for cases with and without a hump and are distributes at selected vertical and horizontal planes. From the studies, we find that the tendency of flow separation and eddy motion are considerably reduced with the use of hump. These occur because here the flow is accelerated over the hump and as a consequence, the adverse pressure gradient which could have cause flow separation diminishes. A hump in the vertical can be easily introduced into the bed of existing channel expansion, and would economical from construction point of view as compared to that of modification of horizontal shape of existing expansions. The results presented in this thesis are of practical values for the optimal hump design.

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A= Area$\left(m^2\right)$

b_1= upstream channel width at CS1 (m)

b_2= channel width at the entrance to an expansion, CS 2 (m)

b_3= channel width at the exit of an expansion, CS 3(m)

C = log- layer constant (-)

c_f= wall shear stress coefficient (-)

E_1= specific energy at CS 1(m)

$E_{d/s}$= percentage in area occupied by eddies between the downstream end of an expansion and the downstream end of a model channel (%)

E_{ex}= percentage in area occupied by eddies in an expansion (%)

E_l= percentage in area occupied by eddies to the left sidewall (to an Observer facing downstream)

E_r= percentage in area occupied by eddies to the right sidewall (to an Observer facing downstream) (%)

F = volume fraction (-)

f_a = volume of fraction for air (-)

F_r= Froude number (-)

h = vertical distance between the water surface and the point of interest (m)

h_e= energy loss due to flow separation and eddy motion (m)

h_f= energy loss caused by friction (m)

h_L= energy loss in the expansion (m)

k = turbulence kinetic energy (m^2/s^2)

k_E= energy loss coefficient (-)

L = characteristic length (m)

L_1= upstream channel section length (m)

L_2= expansion length (m)

L_3= downstream channel section length (m)

P = Reynolds-averaged pressure (N/m^2)

p = instantaneous pressure (N/m^2)

P_r= turbulence production term

Q = total discharge (m^3/s)

q = discharge per unit width(m^2/s)

R_e= Reynolds number (-)

r = width ratio (-)

S_{ij}= mean flow strain rate ($\frac{1}{s}$)

t = time (s)

u = flow velocity (m/s)

U = Reynolds averaged velocity component (m/s)

u'= velocity fluctuation component (m/s)

u^+= near wall velocity (m/s)

U_t=velocity tangent to the wall at a distance of$\Delta y$from the wall (m/s)

u_τ= friction velocity (m/s)

U_0= characteristic velocity (m/s)

y^+ = dimensionless distance from the wall (-)

v_1= cross sectional mean flow velocity at CS1 (m/s)

v_2= cross sectional mean flow velocity at CS2 (m/s)

$\overline{V}_a$= average velocity after the entrance to an expansion (m/s)

V_b=average velocity before the entrance to an expansion (m/s)

$V_{min,a}$= minimum velocity after the entrance to an expansion (m/s)

$V_{min,b}$= minimum velocity before the entrance to an expansion (m/s)

Vor_{high}= percentage in area of high-vorticity region at the entrance to an expansion (%)

Vor_{left}=percentage in area of high-vorticity region to the left of an expansion (to an observer facing downstream) (%)

Vor_{right}= percentage in area of high-vorticity region to the right of an expansion (to an observer

y = depth of flow (m)

y_1= depth of flow upstream of an expansion or at CS 1 (m)

y_2= depth of flow at the entrance to an expansion or at CS 2 (m)

Δy = distance from the wall (m)

Δz_{max}= maximum allowable elevation difference (m)

α= angle of divergence ($^\circ$)

δ = boundary layer thickness (m)

ε = turbulent dissipation (m^2/s^3)

η_1 = elevation above the channel bed (m)

κ = Karman constant (-)
μ = dynamic viscosity of water (Ns/m^2)
ν_t =kinematic eddy viscosity (m^2/s)
ρ_a = density of air (kg / m^3)
ρ_w = density of water (kg / m^3)
τ_{ij} = shear stress tensor (N/m^2)
τ_w = wall shear stress (N/m^2)

$\tau\,\omega$ = specific dissipation, parameter in the $k\!-\!\omega$ turbulence model ($\frac{1}{s}$)

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Chapter One

Introduction

1.1 Background

In general, channel transitions are defined as changes in cross-sectional area in the direction of open channel flow. Transitions can also include changes in bed level. A channel expansion is a transition that connects a relatively narrow upstream channel-section to a wide downstream channel-section. Such a transition is an important component of many hydraulic structures. Due to an increase in cross-sectional area, channel expansions cause flowing water to decelerate. Under steady flow conditions, flow deceleration will lead to an increase in water pressure that in turn triggers flow separation and creates turbulent eddy motions. These turbulent eddy motions can exist over a long distance downstream of the transition. They cause undesirable energy losses and sidewall erosion.

In order to control energy losses and erosion, we need to improve our understanding of the problem of flow in a channel expansion. This problem has not been thoroughly investigated in the past. A lack of thorough knowledge about the problem has motivated this study. From the energy conservation perspective, it is particularly important to be able to reduce or even eliminate areas of turbulent eddy motions in the expansion.

The problem of turbulent flow in an open channel expansion is very complicated, with turbulent eddy motions, flow separation and so on. It is difficult to use the analytical approach to obtain solutions to the problem even under highly simplified conditions. The experimental approach may be taken to tackle the problem, but experiments are very expensive to carry out. Therefore, it may not be feasible to experimentally investigate the effects of many factors that potentially control the behaviour of flow in a channel expansion. In this study, the CFD modelling approach is taken. This approach permits an efficient and systematic exploration of the effects of such factors as the angle of divergence, the crest height of a hump fitted at the channel bed and the Froude number on the flow in an expansion. The idea of using a hump in the vertical to reduce eddy motions and flow separation in expansions is interesting, because it is an easier and more economic solution compared to optimising the horizontal shape (or the sidewalls) of existing expansions.

This study focuses on subcritical flows (with the Froude number less than unity) as they prevail in open channels. A number of important questions need to be answered. How does the flow field, in particular the distribution of eddy motions, vary with the angle of divergence? How does the velocity field change with elevation above the channel bed? Qualitatively, the use of a hump fitted at the channel bed is known to help reduce flow reversal and eddy motions, but quantitatively, how efficient is the use of it? Will answers to the above questions be different at different Froude numbers?

1.2 Specific objectives

The objectives of this study are

- To numerically simulate subcritical flow in channel expansions with different angles of divergence. We will consider an angle of divergence equal to 10.34º, 7.54º and 5.04º in order to match experimental conditions. This will allow data comparison.

- To quantify areas of eddy motions (at different cross-sections and longitudinal planes).

- To investigate the effects of the Froude number.

- To determine the effectiveness of fitting a hump at the channel bed to suppress eddy motions and flow separation. We will consider two simple humps: one with a crest height of 1/4″ (or 0.00635 m, with $\Delta z / y \quad 2.54\%$), and the other with a crest height of 1/3″ (or 0.00838 m, with $\Delta z / y \quad 3.35\%$). These selections are consistent with experimental setup used in previous studies.

1.3 Scope of the work

To achieve the above-mentioned objectives, the rest of this thesis is organized as follows. Chapter 2 gives a summary of previous studies on the topic of flow in expansions, including experimental and analytical studies on flow separation and the formation of turbulent eddies. Previous works on other established facts concerning the design of hydraulically efficient channel expansions are reviewed in this chapter. This chapter also summarises previous studies about the effects of a hump in the vertical on the reduction of eddy motions and flow reversal.

Chapter 3 describes the modelling methodologies used in this study. This chapter provides the theoretical background and fundamental concepts of CFD modelling of free surface flow. The k-ω turbulence model is explained in details, and reasons for choosing this model are discussed. Details of the boundary conditions, including conditions at inlet, outlet, bottom and sidewalls of the model channel are discussed. Also, the choice of meshes, including volume mesh and inflations (near bottom and sidewalls) for accuracy improvement is discussed in this chapter.

In Chapter 4, the energy principle and the concept of specific energy for flow in channel expansions are discussed, together with the concept of E-y curve. The expected behaviour of flow in channel expansions and over a hump is also explained.

Chapter 5 presents the numerical results of the flow field in a flat-bottom expansion and expansions with a 1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) or 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%) hump. The results include velocity, flow streamlines, and along-channel velocity contours at different cross-sections along the length of expansions. In longitudinal planes at different elevations above the channel bed, areas of eddy motions are determined. In cross-sections, eddy motions are evaluated as regions where flow reversal occurs. Percentages in area of low-velocities and high-vorticity areas are evaluated. A comparison of the percentages between a flat-bottom expansion and expansions with a 1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) or 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%), are made. This chapter also discusses the effects of the Froude number, ranging from 0.3 to 0.7.

In chapter 6, we draw conclusions and make suggestions for future work.

Chapter Two

Literature Review

2.1 Experimental studies of subcritical flow in expansions

Previously, a number of researchers have experimentally studied the problem of subcritical flow in expansions. Alauddin and Basak (2006) took the experimental approach to study flow separation in an expanding transition and further downstream. The purpose was to design an expanding transition with minimum flow separation and hence small energy head losses. The authors made measurements of velocity profiles at the inlet, in the expansion, and at the outlet of a sudden expansion, and determined a transition profile closely matching to the shape of separating streamlines in the expansion. Presumably, using the transition profile to build an expanding transition diminishes the energy-dissipating effects of eddies associated with flow separation.

Alauddin and Basak (2006) reported that such an expanding transition gave an overall efficiency of 80.3%, representing an improvement from previous work. The overall efficiency is defined as the ratio of the potential-energy gain to the kinetic-energy loss as water flows through the transition. A higher efficiency means less energy head losses. Alauddin and Basak (2006) suggested that all other existent transitions had a lower efficiency because of their abrupt ending at the downstream end. They concluded that the provision of a smooth outlet by their transition profile was the key to virtually eliminate flow separation and eddy formation.

2.2 Channel expansions fitted with a local hump

Ramamurthy and Basak (1970) conducted an experimental study of flow separation in an expanding transition and the suppression of flow separation by fitting a simple hump at the channel bottom. Flow through expansions would encounter an adverse pressure gradient, decelerate, and therefore separate from the sidewalls. As a result, turbulent eddies form along the sidewalls and cause flow energy dissipations. Ramamurthy and Basak (1970) showed that both the angle of divergence and the length of transition relative to the inlet dimension have effects on flow separation. They also showed that inserting a hump in the bottom profile could suppress flow separation. As they explained, the specific energy head remains the same before and after a horizontal transition, if the energy losses due to friction are negligible. In the presence of a hump, there is a loss of velocity head up to the crest of the hump, and a gain of velocity head after passing the crest.

The results of Ramamurthy and Basak (1970) were based on measurements of depth and velocity at a number of selected sections including the entrance and exit sections of the transition. Without a hump, the flow became more turbulent and asymmetric at a larger Reynolds number, and even with a hump, the same asymmetry appeared at large Reynolds numbers, as revealed by velocity contours. Flow separation was reduced or eliminated after inserting a hump. In conclusion, expanding transitions fitted with a hump perform well in terms of flow energy conservation. The experimental investigation of Ramamurthy and Basak (1970) was limited to a couple of humps with specific crest heights.

2.3 Flow patterns in a channel expansion

2.3.1 Asymmetric behaviour of flow in symmetric expansion

Some previous researchers of fluid flow in expansions have dealt with the case of sudden expansions (see e.g. Mehta 1979, 1981; Graber 1982; Nashta and Garde 1988; Manica and Bortoli 2003). The results reported in their studies highlighted the effects of different expansion ratios on mean flow velocities, fluid pressure distributions and turbulence characteristics. Specially, the asymmetric behaviour of the flow field in perfectly symmetric expansions is very important. First, Abbott and Kline (1962) observed asymmetric flow patterns in their experimental investigations. They also found that the Reynolds numbers and turbulence intensities have no effect on flow pattern. Filetti and Kays (1967) found that the flow in rectangular channel with expansion ratios of 2.125 and 3.1 is asymmetric.

Also, Mehta (1979) conducted an experiment with a two-dimensional rectangular channel and found that the flow is symmetric at an expansion ratio of 1.25 and asymmetric at expansion ratios of 2.0, 2.5 and 3.0. He also found that the expansion ratio has an important effect on asymmetrical behaviour of channel expansions. According to Graber (1982), flows are symmetric in symmetric, two-dimensional rectangular channels with the expansion ratio of less than 1.5. He presented the cause of the asymmetric behaviour of the flow is a static instability of the flow system.

The stability of the system depends on the forces acting on the system and their variation as the system undergoes a small deflection. If the change in stabilizing momentum reaction exceeds the change in the destabilizing pressure force, the system is stable. If not, the asymmetric behaviour of the flow would be expected. The results of the stability analysis of Graber (1982) show that channels have the limitation that the maximum Froude number is less than 0.2. The result also predicts instability for expansion ratios greater than 1.5 that is in good agreement with experimental observations.

Manica and Bortoli (2003) considered laminar flow with low Reynolds number in a symmetric sudden expansion (Figure 2.1). Their numerical results show that below a certain critical Reynolds number (about 50), the flow pattern is symmetric about the channel central line; the two vortices in the expansion corners are more or less of the same size. The symmetric flow pattern becomes unstable at Reynolds number above the critical value. Pair of steady asymmetrical vortices appears as one recirculation region grows at the expense of the other.

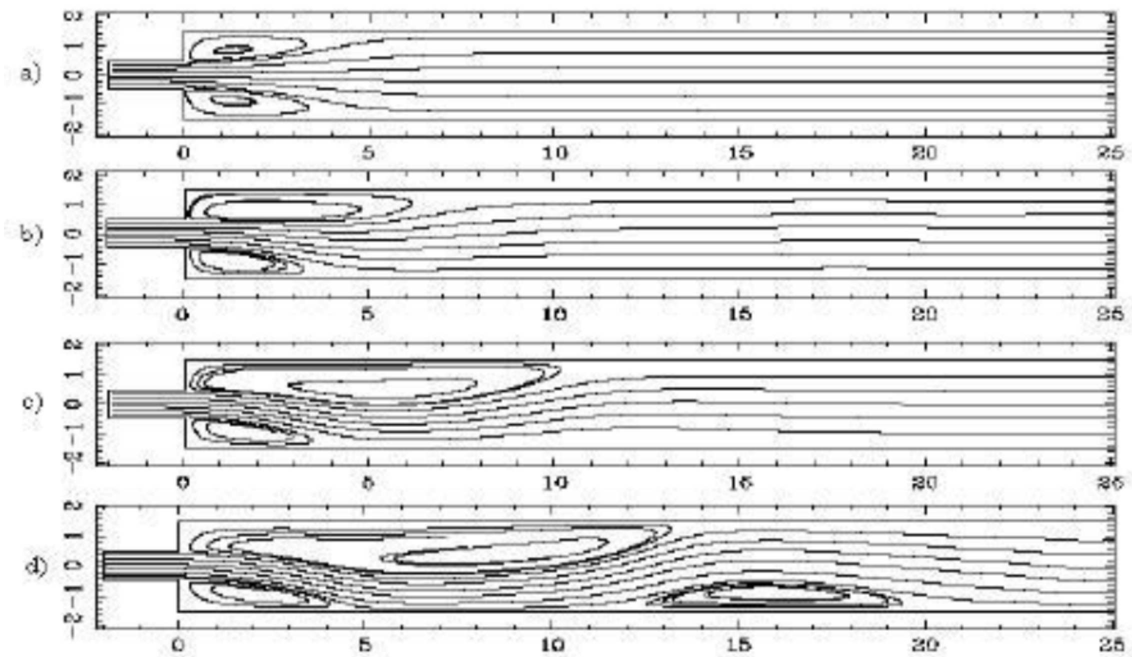


Figure 2.1 Streamlines computed for flow in a 1:3 symmetric sudden expansion. The Reynolds number Re is: (a) 40, (b) 50, (c) 80, and (d) 140. The flow patterns are symmetric when Re = 40 in (a) and asymmetric when Re ≥ 50 in (b-d) (from Manica and de Bortoli, 2003).

2.3.2 Flow characteristics in expansions

Mehta (1979, 1981) showed that flow separation can take place on both sides of the expansion with the maximum velocity line deviating from the centerline of the expansion. Mehta (1979) investigated flow separation in two-dimensional, sudden rectangular channel with width ratios ranging from 1.25 to 3.0, using numerical model and experiments.

The experimental investigations covered both symmetric and asymmetric flow patterns. Mehta (1979) reported that flows in two-dimensional sudden expansions are asymmetric and unstable, with three-dimensional character when the expansion ratio is larger than 1.25;

Reynolds number in the range of 0.5 to 1.0×10^5 has no influence on the asymmetric behaviour of the flow. Also, unequal pressure occurs in eddy pockets on both sides of the axis of symmetry. All the important parameters of flow are influenced by the expansion ratio.

Mehta (1981) conducted an experimental study of the behaviour of the mean flow pattern and the turbulent characteristics for two-dimensional flow through large, sudden expansions. The flow patterns become more asymmetric and unsteady with increasing expansion ratios, whereas the degree of turbulence does not change except the peak values develop earlier and decay faster compared to cases of low expansion ratio.

Seetharamiah and Ramamurthy (1968) presented the idea of using a triangular sill in a channel expansion to decrease separation and eddy formation downstream of the expansion. The sill increases the transition length, and therefore reduces the sharpness of deceleration. They assumed that the amount of energy losses over the sill is negligible and showed two stages of deceleration of subcritical flow in the specific energy diagram. Seetharamiah and Ramamurthy (1968) also pointed out that the geometry of the sill can be chosen such that the theoretical retardation is nearly uniform along the sill, although it can be chosen to accelerate the flow up to the crest of the sill in canals where to reducing silting resulting from deceleration in the transition is very important.

Swamee and Basak (1991) presented a design method for subcritical expansions for rectangular channels, in order to achieve a minimum head loss. By analysing a large number of profiles, they obtained an equation for the design of rectangular expansion, producing the optimal bed-width profile.

Swamee and Basak (1992) discussed an analytical method for the design of expansions that connect a rectangular channel section with a trapezoidal channel section for subcritical flow. They suggested that flow separation in the expansion and the associated energy losses were considerably reduced through the optimal design of bed-width as well as side-slope profiles, on the basis of the momentum and energy equations. They claimed that the optimal profiles represent an improvement from the design of Vittal and Chiranjeevi (1983) in terms of reducing flow head losses. Swamee and Basak (1993) used the optimal control theory for the design of rectangular-to-trapezoidal expansions for gradually varied subcritical flow. They obtained equations for bed-width, side-slope and bed profiles based on the minimization of the transition head losses.

Escudier *et al.* (2002) conducted an experimental study of turbulent flow in a sudden expansion with an expansion ratio of 4 and an aspect ratio of 5.33. A laser Doppler anemometer was used to measure mean flow velocity fluctuations and the Reynolds shear stress. They reported that the flow downstream of the expansion is asymmetric. They concluded that the effect of inlet of expansion is the reason for asymmetrical behaviour of flow.

2.4 Geometric shape of expansions

As shown in Figure 2.2, channel expansions can be classified into five categories, namely, straight line expansions, square end expansions, cylindrical quadrant expansions, warped expansions, and wedge expansions.

Hinds (1927) considered different empirical design methods for various geometries of flumes and siphons. The design criterion was to minimize the transition length and energy losses. To achieve this objective, Hinds (1927) assumed a water-surface profile as two reversed parabolas with equal length, merging tangentially with the upstream and downstream water surface. The energy principle was used to expresses the expanding width as a function of the distance from the inlet of the expansion, with an assumed energy loss coefficient. Hinds (1927) concluded that an S-curved warped wall expansion is the most suitable one.

Smith and Yu (1966) examined the results of Hinds (1927) and found that the S-curved warped wall expansion is inefficient results, and causes flow separation. Smith and Yu (1966) recommended a straight walled diverging expansion (Figure 2.2, “straight line” type).

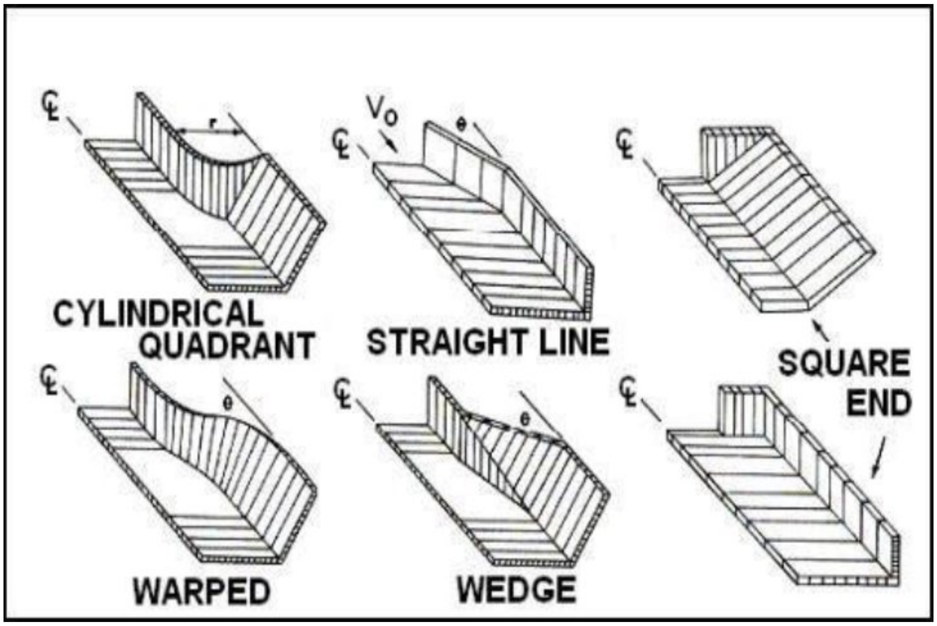


Figure 2.2 Channel expansion types (from U.S. Department of Transportation 1983, Chapter 4). All the expansions have geometry symmetric about the centerline.

2.5 Energy loss analyse for expansions

Using a rational method based on the concept of specific energy, Vittal and Chiranjeevi (1983) attempted to determine the boundary shape of expansions and flow conditions, with minimum head losses. Through experiments, they derived functions for the geometric features of expansions such as the bed width, bed elevation and sidewall slope. Their method was for designing a trapezoidal expansion.

When subcritical flow passes through an expansion, there is a decrease in velocity and an increase in pressure. Without any change in bed level, the water surface will rise by a vertical distance that is equal to the amount of drop of velocity head between the entrance and exit of the expansion. This means a conversion from kinetic to potential energy. However, this conversion is accompanied by energy losses. Mathematic analyses of energy losses in expansions of arbitrary geometry are difficult to perform. Therefore, it is a good alternative to find the energy losses for specific expansions and then extend the results by careful interpolations. Kalinske (1944) found that the rate of loss of energy in a 30° expansion is more than that in a sudden expansion. He found a major portion of the energy in the expansions is lost by direct conversion into heat at the high shear region in the fluid, and the total loss of energy is much higher than the turbulence energy.

Using the energy principle, Skogerboe *et al.* (1971) expressed the head loss in an expansion as a function of the velocity head at the entrance of the expansion. However, there was a small head loss correction which will varied for each expansion. The head loss coefficient was expressed as a function of the inlet Froude number as well as the expansion ratio, instead of a function of the specific energy ratio, as suggested by other researchers.

Skogerboe *et al.* (1971) argued that since a unique relationship exists between the head loss coefficient and specific energy ratio for any particular geometry of open channel expansion, and since a unique relationship between the specific energy ratio and the inlet Froude number, a unique relationship exists between the inlet Froude number and head loss coefficient for any particular expansion geometry. This means that the Froude number is a factor to consider.

As stated in Morris and Wiggert (1972, p. 185), the efficiency of energy conversion requires the flow profile to be continuous and as smooth as possible. Also, the profile should be tangent to the water-surface curves in the upstream and downstream sections of the expansion. In summary, for the design of expansions, the water-surface profile is computed using the energy principle. The accuracy of computations relies on more or less guessed energy losses.

2.6 Hydraulic behaviour of channel expansions

An expansion with a large amount of change of the differential kinetic energy to potential energy is considered to be hydraulically efficient. In fact, the rise of the water surface or the recovery of energy head is less than the theoretical vertical distance (Hinds 1927). Smith and Yu (1966) considered expansions as gradual if the total central angle between sidewalls, α, is smaller than 28°10'. Separation can occur when α reaches 19°, except at the expansion ratio less than 2. Note that α = 28°10' corresponds to a 1:4 ratio of flare; this is a rapid expansion. Except when the expansion ratio is between 1 and 2, separation cannot be avoided. However, reducing α to avoid flow separation in an expansion is not practical because the length of the expansion will increase and the cost to build such an expansion is high.

According to Smith and Yu (1966), in a rapid expansion, flow from contracted section leans toward one of the sidewalls and a large turbulent eddy forms between the jet and the other sidewall. A straight wall flare is better than curved wall flare of equal length (Smith and Yu, 1966), because when the curved wall flare is used, the central angle between wall tangents continuously increases, and the flow may separate on one side of the expansion when the central angle becomes too large. They concluded that the same benefit could be obtained at less cost by using a shorter gradual expansion so that there is no justification for using the rapid expansion.

Kalinske (1944) found that the rate of loss of energy in a 30° expansion is more than the sudden expansion. The author indicated that a major portion of the energy in the expansion is lost by a direct conversion into heat at the high shear region in the fluid, and the total loss of energy is much higher than the turbulence energy.

Chapter Three

Modelling Methodologies

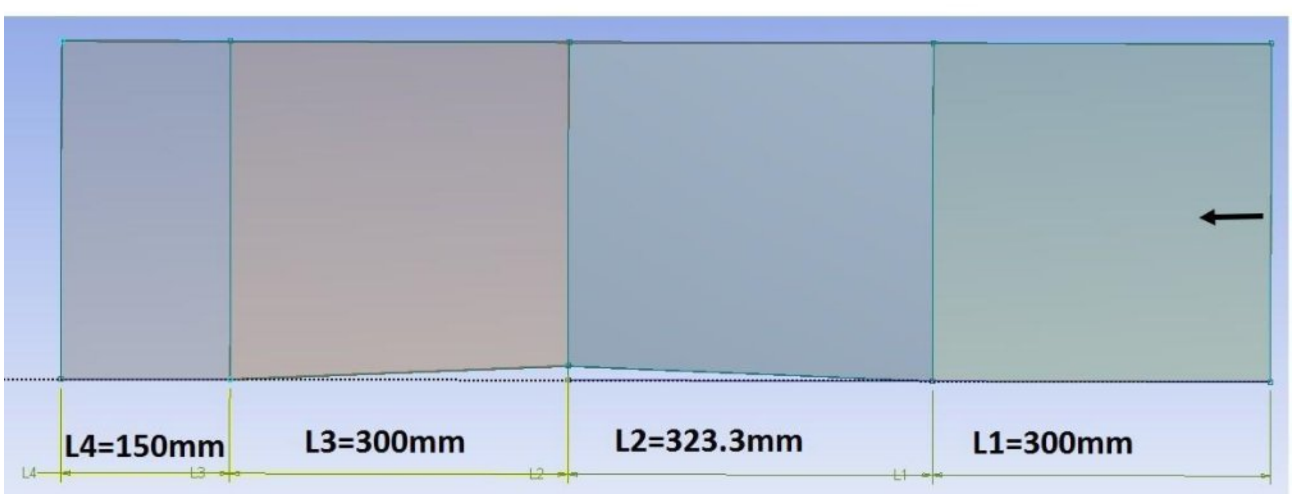
This study aims to model subcritical turbulent flow in the expansion section of an open channel. CFX software (ANSYS 2016) was used to create an appropriate model channel of different geometric configurations and to predict the three orthogonal components of water velocity along with the depth of flow in the model channel. This chapter begins with a description of the model domain. Then, the hydrodynamics equations and turbulence closure schemes are presented. This is followed by specifications of boundary and initial conditions. Next, strategies for the generation of finite volume meshes for flow computation are discussed.

3.1 Model domain

The model domain for flow computations consists of an upstream channel section, an expansion and a downstream channel section, with or without a hump fitted at the channel bottom of the expansion section (Figure 3.1). In some cases, the model domain allows for an additional extension channel section at downstream.

The velocity and pressure fields of steady state are computed for given conditions of inflow at the upstream end and outflow at the downstream end of the model channel. Inclusion of an upstream channel section of efficient length allows the development of realistic flow profiles or vertically distributed flow velocities that approach the expansion, whereas inclusion of a downstream channel section is helpful for removing possible end effects, which are artificial, on the computed flow field in the expansion.

(a) Elevation



(b) Plan view

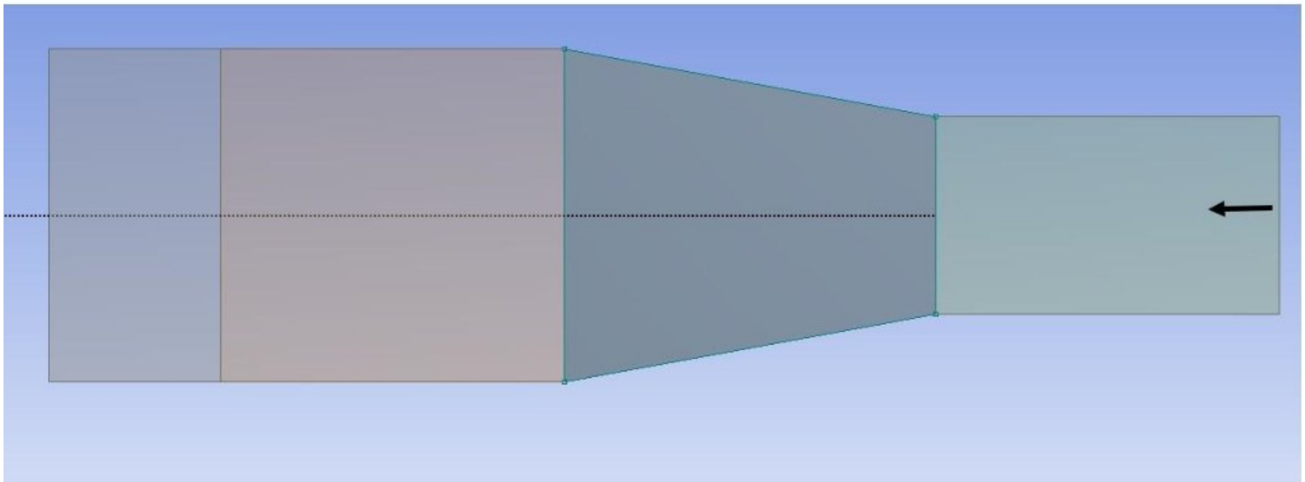


Figure 3.1 Geometry of the model channel, showing dimensions of various channel sections and bottom configurations. Uniform water flow enters (arrow) the model channel from the relatively narrow channel section.

3.2 The volume of fluid method

The interface between the gas and liquid, where the difference in density between these two phases is quite large, is considered as a free surface. The inertia of the gas could usually be neglected due to a low density. Therefore, the only influence of the gas is the pressure acted on the interface and it is not necessary to model details of the gas phase. Hence, the free surface is simply modelled as a boundary with constant pressure.

The volume of fluid method is used to determine the shape and location of free surface based on the concept of a fractional volume of fluid. A unity value of the volume fraction corresponds to a full element occupied by the fluid (or liquid), and a zero value indicates an empty element containing no fluid (or gas). A value of volume fraction between zero and one means that the corresponding element is the surface (or partial) element. The equation of the volume of fluid method for determining the shape of the free surface is given by

$$\frac{\partial F}{\partial t} + U\frac{\partial F}{\partial x} + V\frac{\partial F}{\partial y} + W\frac{\partial F}{\partial z} = 0 \qquad (3.30)$$

where F is the volume fraction.

3.3 Boundary conditions

The appropriate use of boundary conditions is required to fully define the fluid flow problem. The external boundaries of the model domain are the inlet, outlet, sidewalls and channel-bed.

3.3.1 Inlet condition

Inlets are used mostly for regions where inflow is expected. At the inlet where the fluid flows into the domain (Fig. 3.1), the imposed mass and momentum conditions is the normal speed v_n. The magnitude of the inlet velocity is specified and the direction is taken to be normal to the boundary. The normal speed is steady and uniform. For instance, v_n equals 0.78 m/s for some simulations. Also, the relative pressure at the inlet is specified

$$P \quad (\rho_w - \rho_a) g F_w (\eta_1 - z) \tag{3.31}$$

where the subscripts w and a indicate water and the air, respectively, g is gravity, η_1 is the elevation (above the channel bed) of the free surface at the inlet, and z changes from zero at the channel bed to η_1 at the free surface. A value for η_1 is given (e.g. η_1 = 0.25 m for some simulations).

At the inlet, the turbulence intensity and turbulence length scale are specified. The turbulence intensity is given in terms of a fractional intensity (5%), and the turbulence length scale is taken to be equal to η_1.

3.3.2 Outlet condition

At the outlet where the fluid leaves the model domain (Fig. 3.1), the appropriate condition to impose is the relative static pressure, given by

$$P \quad (\rho_w - \rho_a) g F_w (\eta_2 - z) \tag{3.32}$$

where η_2 is the elevation (above the channel bed) of the free surface at the outlet, and z changes from zero at the channel bed to η_2 at the free surface. Usually, η_2 must be known as part of the problem definition. For the case of flows in expansions, the elevation is not known in advance.

However, it is sufficient to provide an estimate of η_2 using the energy principle (Henderson 1966) for the purpose of determining the distribution of the relative static pressure with depth below the free surface.

3.3.3 Solid surface condition

Channel sidewalls and the channel bed (Fig. 3.1) are solid surfaces where conditions to be imposed can be a no-slip wall, a free slip wall or specified shear. In this study, the no-slip wall condition is applied. The flow near to the no-slip wall is modelled using wall function approach. Based on the wall function approach , the near wall tangential velocity in the log-law region is related to the wall-shear-stress , τ_w , by means of a logarithmic relation. The logarithmic relation for the near wall velocity is given by

$$u^{+} = \frac{U_t}{u_\tau} = \frac{1}{\kappa}\ln\left(y^{+}\right) + C \tag{3.33}$$

where

$$y^{+} = \frac{\rho \Delta y u_\tau}{\mu}, \tag{3.34}$$

$$u_\tau = \left(\frac{\tau_w}{\rho}\right)^{1/2} \tag{3.35}$$

u^{+} is the near wall velocity , U_t is the known velocity tangent to the wall at a distance of Δy from the wall, u_τ is the friction velocity, y^{+} is the dimensionless distance from the wall, τ_w is the shear stress of the wall, κ is the von Karman constant, and C is the log-layer constant that depends on the wall roughness.

3.4 Initial conditions

Let h_w denote the initial depth of water. Initially, the volume of fraction for air is given by a step function $f_a = \chi(z - h_w)$, where z is the vertical coordinates pointing upward with z = 0 at the channel bed. The step function χ gives $f_a = 1$ for $z - h_w > 0$, and $f_a = 0$ for $z - h_w \leq 0$. The initial volume of fluid for water is $f_w \quad 1 - f_a$. Initially, the relative pressure field, P, in water is

hydrostatic or $P \quad \rho_w \, g(h_w - z)$ and is uniformly zero in the air (the pressure in the air is set to

zero). Thus, the initial conditions for the pressure field and the volume fraction are consistent.

3.5 Finite volume meshes

It is desirable to use fine meshes for flow computations in order to capture detailed flow features such as eddies and velocity shears. Meshes were generated on the basis of a number of criteria: First, meshes are fine enough in order to resolve rapid spatial variations in the velocity fields, especially near wall boundaries. This requirement is satisfied by performing inflation on meshes adjacent to solid walls where eddies and velocity shear are expected to appear (Fig. 3.2).

Second, the structure of meshes used for flow computations must not affect the computational results. In other words, the model results produced should be independent of the configurations of the meshes used. The strategies used to satisfy this requirement were to several mesh systems of progressive fine sizes (e.g. $10*10^{-3}$ m, $7*10^{-3}$ m, $5*10^{-3}$ m and $4*10^{-3}$ m) and to carry out model runs using the different meshes under identical flow conditions. The independence of the computed flow field for these runs was verified through comparisons of the results among these runs.

Third, the total number mesh points must not be excessively larger, resulting in prohibitively high computation cost. An excessively large number of mesh points will also create difficulties in the post processing of model output.

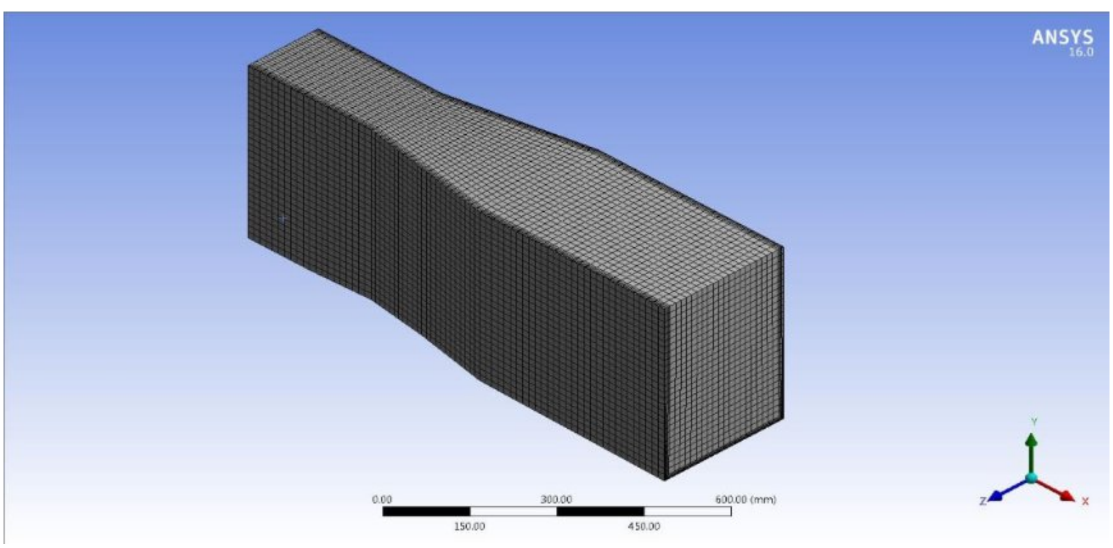


Figure 3.2 A sample finite volume mesh system used for flow computations, showing the inflation of meshes near all solid walls. The solid surface on the top is set to be slippery.

Chapter Four

The Energy Principle

4.1 Energy balance for flow in expansions

In this study the expansion connects a cross section of rectangular shape with a smaller width to a cross section of rectangular shape with a larger width. Figure 4.1 shows the plan view of the channel expansion. The width of the expansion changes from b_2 at its upstream end (CS2) to b_3 at its downstream end (CS3) .With the assumption of hydrostatic pressure, an energy equation could be written between sections CS2 and CS3, as below:

$$z_2 + \frac{v_2^2}{2g} + y_2 \quad z_3 + \frac{v_3^2}{2g} + y_3 + h_L \tag{4.1}$$

where g is the gravity; y_2 and y_3 are the depth of flow ; v_2 and v_3 are the cross sectional mean flow velocity; z_2 and z_3 are the height of the bed above datum ; h_L is the energy loss in the expansion; the subscripts 2 and 3 refer to CS2 and CS3 , respectively.

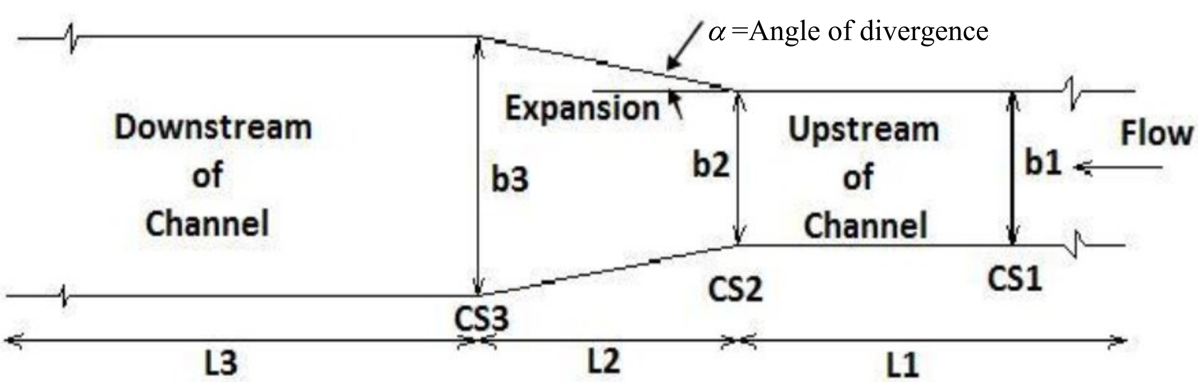


Figure 4.1 Plan view of a channel expansion.

If the channel bed is at the same level, z_2 and z_3 are the same. Also if h_L is neglected, Equation (4.1) will be simplified

$$y_2 + \frac{v_2^2}{2g} \quad y_3 + \frac{v_3^2}{2g} \tag{4.2}$$

Equation (4.2) shows that the flow at the two cross sections has the same specific energy. The term h_L in equation (4.1) is the energy loss in the expansion, including the energy loss h_f due to friction at the channel bed and on the sidewalls, and the energy loss h_e due to flow separation and eddy motions. h_e is expected to be much larger than h_f .Therefore, h_f can be neglected.

$$h_L \approx h_e \tag{4.3}$$

The energy loss, h_e , can be evaluated from

$$h_e = \left(y_2 + \frac{v_2^2}{2g} \right) - \left(y_3 + \frac{v_3^2}{2g} \right) \tag{4.4}$$

For the special case where the channel is rectangular, the discharge per unit width of channel; q, is related to the depth of flow, y, and flow velocity, v, through the equation of continuity,

$$v_2 \quad \frac{q_2}{y_2} \quad , \tag{4.5}$$

$$v_3 \quad \frac{q_3}{y_3} \tag{4.6}$$

Equation (4.4) can be rewritten as

$$h_e = \left(y_2 + \frac{q_2^2}{2gy_2^2} \right) - \left(y_3 + \frac{q_3^2}{2gy_3^2} \right) \tag{4.7}$$

This equation is used for obtaining energy loss in the expansion due to flow separation and eddy motions. An energy loss coefficient can be defined as

$$k_E \quad \frac{h_e}{g_2^2/\left(2gy_2^2\right)} \tag{4.8}$$

4.2 The concept of specific energy

The concept of specific energy is very important in the study of open-channel flows. Using the channel bed as datum, the specific energy, *E*, is defined as

$$E \quad y + \frac{V^2}{2g} \tag{4.9}$$

For the special case where the channel is rectangular, the equation of continuity is given by

$$q \quad \frac{Q}{B} \quad vy \tag{4.10}$$

where Q is the total discharge ; b is the width of the channel. The specific energy equation (4.9) can be rewritten as

$$E \quad y + \frac{q^2}{2gy^2} \tag{4.11}$$

Thus, for a given value of q, we have

$$(E - y)\, y^2 \quad \frac{q^2}{2g} = \text{constant} \tag{4.12}$$

4. 3 E-y curve

Consider water flow at two cross sections (CS2 and CS3) in an expansion, the corresponding per-unit-width discharges are $q_2 = Q/b_2$ and $q_3 = Q/b_3$. Since $b_3 > b_2$, we have $q_3 < q_2$. The state of flow at cross sections 2 and 3 is represented by the two E-y curves (marked by q_2 and q_3, respectively).

The so-called E-y curve (Figure 4.2) shows how E will vary with y for a given value of q in a horizontal channel. More interestingly, as water flows through a channel expansion, the state of flow will change; this is equivalent to moving from one specific energy curve to another.

If there is no energy loss between cross sections 2 and 3, i.e. when the specific energy at cross sections 2 and 3 is the same (represented by the vertical line). The depth of flow, y, (dashed, horizontal lines) will increase from upstream (the E-y curve marked by q_2) to downstream (the E-y curve marked by q_3).

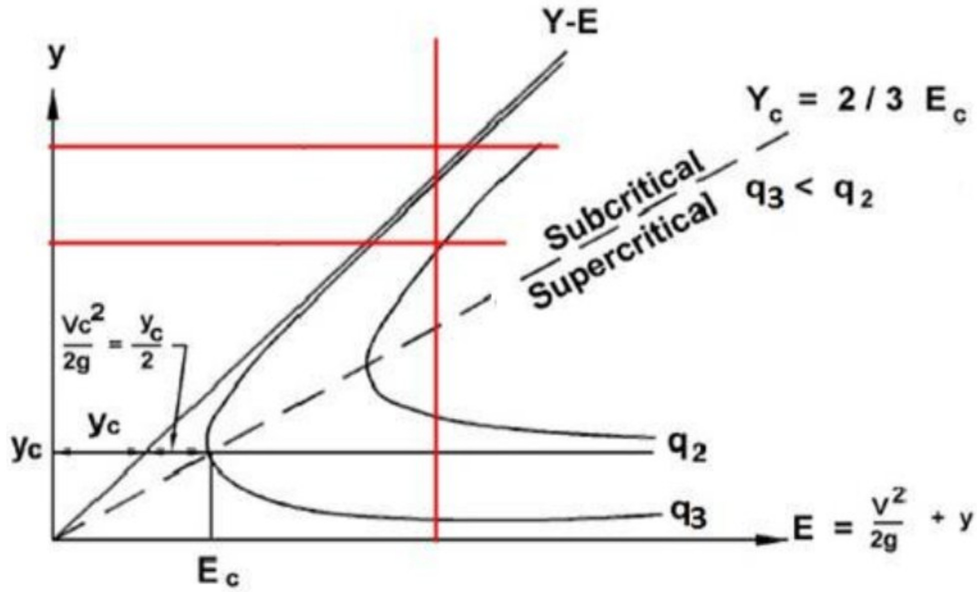


Figure 4.2 The specific energy curve and its application in the expansion problem.

4.4 Critical flow and the concept of the Froude number

The concept of critical flow is graphically illustrated in the E-y curve (Figure 4.2). For a given per-unit-width discharge, the flow is critical when the specific energy of flow is at a minimum level. In a channel expansion when flow at high velocity discharges into a zone of lower velocity, a rather abrupt rise occurs in the flow surface. The rapidly flowing flow is abruptly slowed and increases in height, converting some of the flow's initial kinetic energy into an increase in potential energy (Henderson, 1966).

The specific energy equation (4.9) is valid only for small slopes (< 10%), where the flow has negligible acceleration in the vertical and hence the pressure distribution is hydrostatic. The velocity coefficient is usually quite high, between 0.95 and 0.99 for the rivers. Since the effects of the velocity variations across the flow section are neglected, the velocity coefficient, α , is assumed to be equal 1.0 in this study. This assumption implies that surface waves with high amplitudes are not generated and propagate during the expansion. This could be ensured when the Froude number is less than one at upstream, however, for large Froude numbers, the presence of such surface waves is inevitable.

The Froude number, F_r , is defined as the ratio of actual water velocity, v, to surface wave celerity, $\sqrt{gy}$ .The Froude number at cross section CS1(Figure 4.1) is defined as

$$Fr_1 = \frac{v_1}{\sqrt{gy_1}} \qquad (4.13)$$

The Froude number is only defined for channel sections that have a free surface. When $Fr < 1$, the flow is said to be subcritical; when $Fr > 1$, the flow is said to be supercritical; when $Fr = 1$, the flow is said to be critical.

On the specific energy diagram (Figure 4.2), the parts corresponding to subcritical and supercritical flows are divided by the line $Y_c = \frac{2}{3} E_C$ (the crest point C), below which we have supercritical flow (the lower limb), whereas above which we have subcritical flow (the upper limb). For critical flow denoted by the subscript c, the depth of flow, flow velocity and the specific energy are interrelated as

$$v_c = \sqrt{gy_c} \qquad (4.14)$$

$$y_c = \frac{2}{3} E_c \qquad (4.15)$$

4. 5 Flow over a step in the vertical (hump)

Consider an open channel of constant width but with a change in the bed level such as an upward step and divergence angle α, shown in Figure 4.1. If α is zero, the per-unit-width discharge will not change (Figure 4.3) .In Figure 4.3, CS2 and CS3 are cross sections, upstream of the vertical step and at the vertical step, respectively.

The behaviour of flow over a step in the vertical can be analyzed using the energy principle, written between cross sections CS2 and CS3

$$z_2 + E_2 = z_3 + E_3 \qquad (4.16)$$

where z_2 and z_3 are the bottom elevations at the two cross sections, respectively. The maximum permissible height of step, $\Delta z \quad z_3 - z_1$, is equal to the difference energy, E_2 , and the minimum possible specific energy $(E_3)_{\min} \quad E_c$ for the given per-unit-width discharge, q. Consider subcritical flow, represented by point A on the upper limb of the specific energy curve (Figure 4.4). Subcritical flow approaches the vertical step (hump).

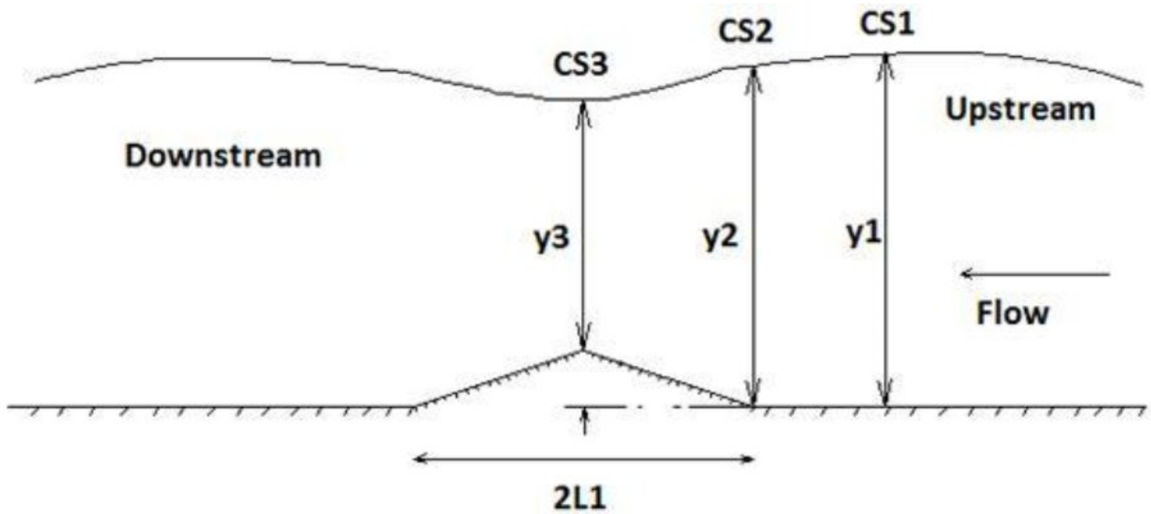


Figure 4.3 Water surface profile for flow over a vertical step (hump) fitted on the bottom of a uniform channel. The depth of flow decreases over the hump on the basis of the energy Principle. From cross section CS 2 to cross section CS 3, the bed level rises and the water pressure decreases; from cross section CS 3 toward downstream, the water pressure increases while the bed level drops.

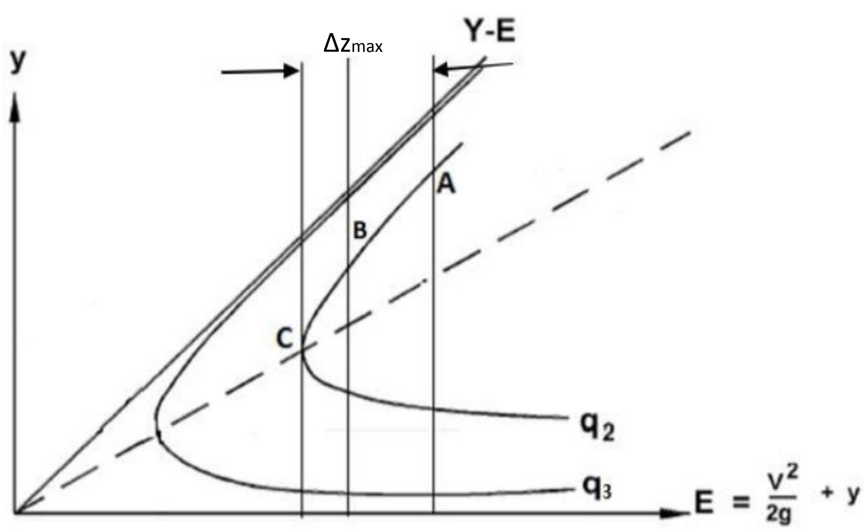


Figure 4.4 Specific energy diagram for a channel expansion.

Point C represents critical flow with the minimum specific energy for the given per- unit -width discharge. Δz_{max} is the maximum permissible difference between the two elevations or the distance between two vertical lines that passes from point A and point C (Figure 4.4) .

We assume a point B on the upper limb of the same E-y curve on which point A is. The distance between the vertical lines that passes through points A and B shows the elevation difference, Δz , being smaller than the maximum permissible value Δz_{max} . Point B represents the flow over the hump and the ordinate of this point shows the depth of flow over the hump. The depth of flow decreases over the hump.

4. 6 Flow in a combination of a horizontal expansion and a vertical step

A vertical step (Figure 4.3) causes the depth of the flow to decrease, whereas an expansion (Figure 4.1) causes the depth of flow to increase. The effects of a hump and expansion have been discussed separately. Now, we consider the effects of an expansion fitted with a hump.

The expanding width and rising bottom (hump) work against each other. A channel expansion causes the flow to decelerate and the depth of flow to increase, whereas a hump causes the flow to accelerate and the depth of flow to decrease. With a combination of two geometric factors, at high Froude numbers, the former is more influential, whereas at low Froude numbers, the latter has dominant effects.

4.7 Limitations on the use of the energy principle

There is a limitation on the use of the energy principle in short channel expansions. First of all, the assumption of zero energy head losses along the length of expansions is questionable. There are energy losses not only due to friction on the sidewalls and at the channel bottom, but also due to eddy motions associated with flow separation.

Second, the depth of flow as well as flow velocity are never uniform across the section immediately following the expanding section, although, after reaching a certain point at some distance downstream, uniform flow conditions can be established again. The second limitation is less problematic if one is interested mainly in the cross-sectionally averaged flow velocity and the depth of flow. However, it is necessary to pay a great attention to this limitation when one deals with flow in boundary layers very close to the sidewalls and the bottom.

Chapter Five

Results

In this chapter we present and compare results for flat bottom channels and channels with a hump. Different flow quantities including the velocity field and vorticity contours at different depths in the expansion length are compared. We consider channel expansions with different angles of divergence, different Froude numbers, and different hump crest heights. Table 5.1 shows the geometric properties of all channel expansions. We examine regions of flow and eddy motions in flat bottom channels, and the effect of humps on reducing the separation region and on the velocity field in the expansion and further down. We further examine the effects of the Froude number varying between 0.3 and 0.7. In all cases, subcritical flows, i.e. flows with Froude numbers less than unity are considered.

5.1 The model channel

The most important section of the channel is the expansion, without or with bottom variation (hump). The specifications of the expansion for different runs and the specifications of the hump fitted in the expansion are listed in Table 5.1. The expanding width and rising bottom (the hump) work against each other. The expanding width causes the flow to decelerate and the depth of flow to increase; whereas the rising bottom causes the flow to accelerate and the depth of flow to decrease. At low Froude numbers, the rising bottom is dominant; whereas at high Froude numbers the expanding width is dominant parameter. Therefore, we expect that humps will be more effective for flows with lower Froude numbers.

Table5.1 Geometric properties of channel expansions used in 13 model runs, for which the Froude number is equal to 0.5.These parameters, include upstream channel width (B1), downstream channel width (B2), upstream channel length (L1), expansion length (L2), downstream channel length (L3), expansion angle (α), downstream extension length (L4), hump crest height (H), and mesh resolution(Δx).

Run	B1 (m)	B2 (m)	L1 (m)	L2 (m)	L3 (m)	α ( )	L4 (m)	H (m)	Δx (m)
FB1	0.172	0.290	0.300	0.3233	0.300	10.34	0	0	0.010
FB2	0.172	0.290	0.300	0.3233	0.300	10.34	0	0	0.007
FB8	0.172	0.290	0.300	0.3233	0.300	10.34	0	0	0.005
FB3	0.172	0.290	0.300	0.3233	0.300	10.34	0	0	0.004
FB4	0.172	0.290	0.300	0.3233	0.300	10.34	0.150	0	0.004
FB5	0.1996	0.2852	0.300	0.3233	0.300	7.54	0.150	0	0.004
FB6	0.2282	0.2852	0.300	0.3233	0.300	5.04	0.150	0	0.004
HQ1	0.172	0.290	0.300	0.3233	0.300	10.34	0.150	0.00635	0.004
HH1	0.172	0.290	0.300	0.3233	0.300	10.34	0.150	0.00838	0.004
HQ2	0.1996	0.2852	0.300	0.3233	0.300	7.54	0.150	0.00635	0.004
HH2	0.1996	0.2852	0.300	0.3233	0.300	7.54	0.150	0.00838	0.004
HQ3	0.2282	0.2852	0.300	0.3233	0.300	5.04	0.150	0.00635	0.004
HH3	0.2282	0.2852	0.300	0.3233	0.300	5.04	0.150	0.00838	0.004

Mehta (1979) reported that in pipe flow experiments, flows in a two-dimensional sudden expansion are asymmetric and unstable, with three-dimensional character, when the expansion ratio is larger than 1.25. In this study, the ratios for different angles are shown in Table 5.2. The expansion with α 10.34° is considered as a gradual expansion because it satisfies the condition

$0.5(B_3 - B_1)/L_2 < 0.25$ (see Chapter 4, Figure 4.1). Nevertheless, since for The angle of divergence of 10.34°, we have B_3 / B_1 1.68 >1.5 , the expansion is expected to be more influential to flow energy losses than the condition (the Froude number) of the upstream flow, as is the case for an abrupt expansion. However, for smaller angles of divergence, i.e. α 7.54° and α 5.04°, the gradual expansion condition as expressed above is satisfied and therefore these expansions are considered as gradual expansions.

Table 5.2 The width ratio for different divergence angles.

α ( )	Width ratio ($\frac{B_3}{B_1}$)
10.34°	1.68
7.54°	1.42
5.04°	1.25

In order to make comparisons between channel expansions without and with a hump, simulations were carried out for channel expansions with a flat bottom and for expansions fitted with humps with a crest height of 1/4" (or 0.00635 m, with $\Delta z / y$ 2.54% , where $\Delta z / y$ is the ratio of the crest height of hump to the height of water at the entrance of the channel) and 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%). An upstream flow depth of 0.250 m is considered for all the runs listed in Table 5.1.

The channel expansion of 0.3233 m in length is short, relative to its width (ranging from 0.2852 to 0.290 m) at the downstream end. For short expansions frictional losses of energy head are not significant, compared to those caused by potential flow separation. According to laboratory experiments (Najafi-Nejad-Nasser, 2011), a 10% energy loss is assumed. Based on this assumed energy loss, elevations at the downstream end of the expansion are found and listed in Table 5.3 for the Froude number of 0.5. Table 5.3 also contains other parameters and boundary specifications of the simulated channels.

The flow simulations consider two fluids: air (at 25º C) and water (with density of 997 kg/m^3). The air interacts with water at the free surface where proper boundary conditions are given in terms of pressure and volume fraction. The volume fraction of air is 1 above the free surface and 0 below, whereas the volume fraction of water is 0 above the free surface and 1 below. At the free surface, the pressure is equal to the atmospheric pressure. Below the free surface, hydrostatic pressure is assumed.

The solution procedures in all the model runs allow a minimum of 100 iterations and a maximum of 200 iterations, with a convergence criterion set to10^{-5}.

We study two types of hump, with a crest height of 1/4" (or 0.00635 m, with $\Delta z / y \quad 2.54\%$), and 1/3″ (or 0.00838 m, with $\Delta z / y \quad 3.35\%$), respectively, for different angles of divergence. Figure 3.1 shows the position of the hump fitted on the channel bottom. The design of the hump is as follows:

The hump begins from the entrance to the expansion. The bottom of the channel expansion has a slope of slightly less than 2% and 4% for 1/4" (or 0.00635 m, with $\Delta z / y \quad 2.54\%$), and1/3″ (or 0.00838 m, with $\Delta z / y \quad 3.35\%$) humps, respectively, which is steep

Table 5.3 Parameters and boundary specifications for nine model runs with the Froude number of 0.5. Solid walls are taken as non-slippery. Turbulence model used is k-ω.

Parameter	FB4	HQ1	HH1	FB5	HQ2	HH2	FB6	HQ3	HH3
Upstream flow depth (m)	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250
Downstream flow depth (m)	0.270	0.270	0.270	0.265	0.265	0.265	0.260	0.260	0.260
Water density (kg/m3)	997	997	997	997	997	997	997	997	997
Normal flow speed at inlet (m/s)	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Turbulence fractional intensity at inlet	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Eddy length scale at inlet (m)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Physical timescale (s)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

compared to typical slopes in natural river channels. The channel bottom is raised linearly, reaching its crest height at the exit of the expansion, and then drops linearly with a favourable slope equal to 2% and 4%, down to the bottom level at the downstream end of the model channel. Variations in the channel bottom are almost symmetric above the downstream end of the channel expansion.

The effects of a longitudinal slope are not important in this study, where the expansions considered are short. Long expansions are expensive to build, although they have smaller angles of divergence and are less likely to trigger flow separation. In short expansions, flow mainly changes in response to changes in channel width at different cross-sections and therefore varying channel width is a more influential parameter than the longitudinal slope. Therefore, we focus on the effects of different angles of divergence.

It is possible to scale up the model expansions discussed in this thesis, because scaling up will not change the angle of divergence, which is the most influential factor. The other influential factor is the dimensionless Froude number. It is possible to keep the same Froude numbers when scaling up.

5.2 Considerations of mesh resolution and downstream channel extension

To ensure that model results are independent of meshes used, water surface profiles for model runs FB1, FB2, FB8 and FB3, where mesh sizes are about 10, 7, 5and 4 mm, respectively, were compared. It was observed that water surface profiles for FB8 and FB3 are close to each other, meaning that a mesh resolution of 5 or 4 mm is sufficiently accurate. To have the best accuracy, 4mm mesh is used for the rest of model runs.

Also we compared the water surface profiles for FB3 and FB4, where FB4 has an extra downstream section of 0.150 m long (see Table 5.1). The water surface profiles were close to each other. However, changes to flow field (including flow depth and flow velocity) in the extended channel may persist over a long distance downstream of the expansion, even though the expansion itself is short. Therefore, for more realistic flow simulations, the model channel with a longer downstream length, i.e. FB4, is used for the rest of simulations.

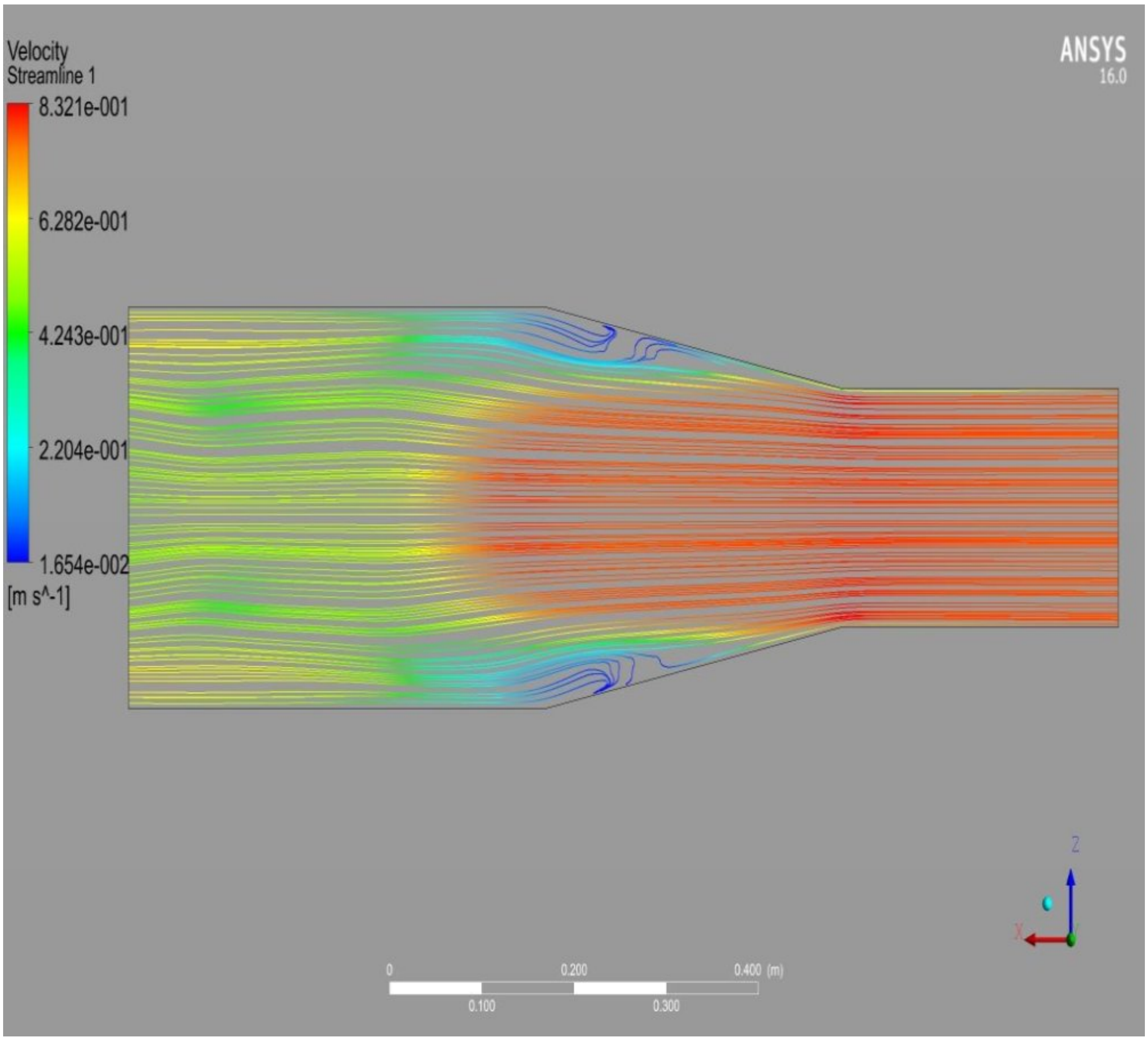
In summary, the 4 mm mesh resolution and the model channel with the extended downstream length, i.e., extended by 0.150 m, is used for simulations.

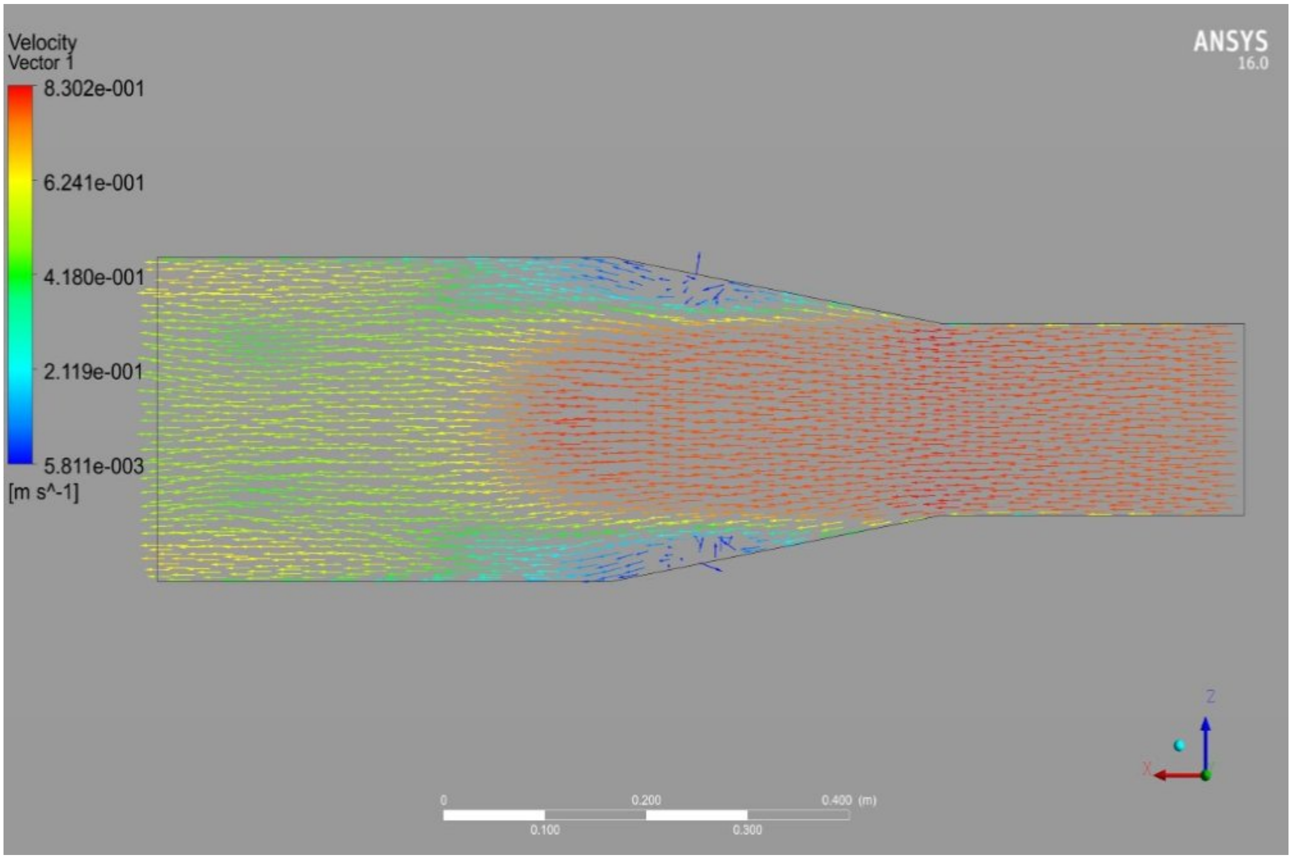
5.3 Velocity field and flow separation for α 10.34° and F_r 0.5

In this section we examine the results of velocity for the channel expansion with α 10.34° (profiles for runs FB4, HQ1, and HH1 in Table 5.1). Figures 5.1a and 5.1b show the velocity field for FB4 (flat-bottom channel). The velocity field is plotted in the xy-plane, at an elevation of 0.230 m above the channel bed. We observe non-uniform water velocities, starting from the entrance to the expansion and continuing until about one-third of the expansion. The velocities decrease in the longitudinal direction as a result of the widening of the channel. The average velocity is 0.804 m/s before the entrance to the expansion and 0.496 m/s in the expansion. The minimum velocity is 0.203 m/s before the entrance to the expansion and 0.005 m/s in the expansion. These small velocities are an indicator of the formation of turbulent eddies.

Regions of eddies (Figures 5.1a and 5.1b) are displayed as the dark blue areas next to the right (to an observer facing downstream) sidewall as well as next to the left sidewall of the expansion. These turbulent eddies result from flow separation from the diverging sidewalls and cause energy losses. In a given xy-plane (i.e. a given elevation above the channel bed), the region of eddy motions is assumed as the flow area where velocities are below 20% of the average velocity for the upstream channel section. This velocity range is consistent with the eddy regions (dark blue area) as shown in Figures 5.1a and 5.1b. For Run FB4, the average velocity is 0.804 m/s, and the corresponding threshold velocity for eddy motion delineation is 0.16 m/s. According to this criterion, eddies in the expansion occupy 10.6 % of the flow area, and eddies occupy 4.5% of the flow area between the downstream end of the expansion and the downstream end of the model channel.

From Figures 5.1a and 5.1b, it is observed that the distribution of eddies is asymmetric. Eddies to the right side are larger than those to the left. The percentages of area, occupied by eddies near the right sidewall (to an observer facing downstream) and near the left sidewall of the channel expansion, are 15.1% and 5.1%, respectively. These values confirm that the eddies are more active near the right sidewall of the channel.





(b)

Figure 5.1 (a) Velocity vectors at an elevation of 0.230 m above the channel bed for Run FB4 for the Froude number of 0.5. The maximum velocity is 0.86 m/s. (b) The close up of velocity vectors in (a). Regions of eddies are observed near both sidewalls.

We found that the region of eddies near the right sidewall begins immediately after the entrance to the expansion and continues up to 4 mm before the exit of the expansion. However, on the left side, the region of eddies begins 0.030 m after the entrance of the expansion and extends up to 4 mm before the exit of the expansion. We observe a difference between the vertical ranges of eddies on the right and left sidewalls. On the right sidewall, eddies are located at a distance of up to 0.0774 m from the channel centerline, whereas on the left sidewall eddies are up to 81.8 mm from the centerline. It means that eddies to the left are closer to the wall or the region of eddies is narrower to the left. The presence of eddies to the right and the left and the asymmetric behaviour are shown in Figure 5.2, where the flow separation (eddies) from both sidewalls are clearly illustrated by velocity streamlines.

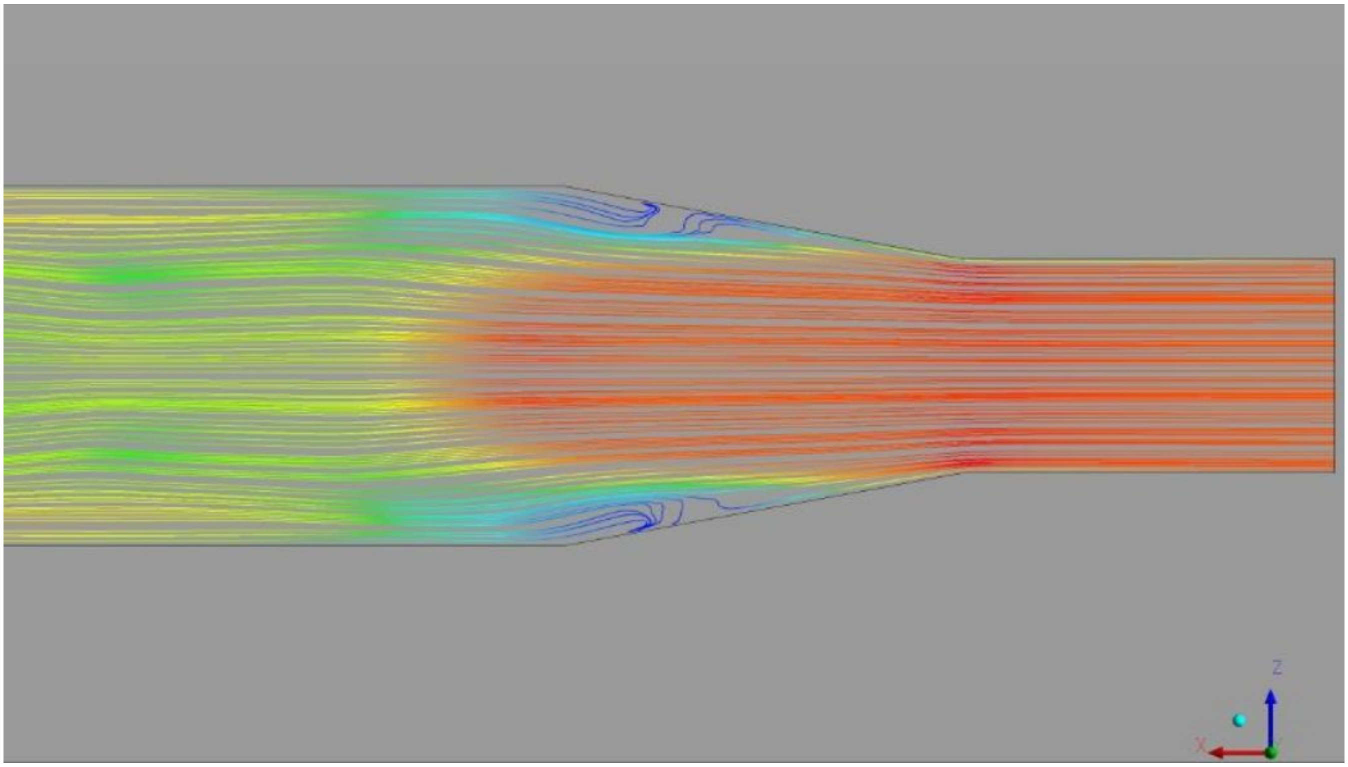


Figure 5.2 Flow streamlines at an elevation of 0.230 m above the channel bed in the expansion for Run FB4. The Froude number is 0.5.

At different elevations above the channel bed, the average velocities exhibit similar features. The average velocities decrease after the entrance to the expansion. The minimum velocities after the entrance to the expansion decrease to very small values. The average velocities are listed in Table 5.4, where h represents the elevation above the channel bed, $\overline{V_b}$ and $\overline{V_a}$ represent the average velocities before and after the entrance to the expansion, respectively. The minimum velocities before and after the entrance to the expansion are also listed in Table 5.5 ($V_{\min,b}$ represents the minimum velocity before the entrance to the expansion and $V_{\min,a}$ represents the minimum velocity after the entrance to the expansion). In all the cases, $V_{\min,a}$ is close to zero, which confirms the presence of eddies at all elevations down to 0.050 m above the channel bed.

The area occupied by eddies (E_{ex} in Table 5.6) in the expansion almost monotonically decreases with decreasing elevation (i.e. toward the channel bed). The area occupied by eddies between the downstream end of the expansion and the downstream end of the model channel ($E_{d/s}$ in Table 5.6) decreases at elevations below 0.230 m and will remain almost the same for different elevations.

The asymmetric behaviour of eddies at different elevations is persistent. The area occupied by eddies to the right is present at all elevations, however, its percentage in area at elevations closer to the surface is larger than its percentage at elevations close to the channel bed, as shown as E_r in Table 5.7. The area occupied by eddies to the left diminishes at elevations below 0.230 m, shown as E_l in Table 5.7. Eddies are more asymmetric close to the channel bed.

Table 5.4 Average velocities at different elevations above the channel bed, before and after the entrance to the expansion for Run FB4.

h(m)	0.230	0.200	0.150	0.100	0.050
$\overline{V}_b\,(m/s)$	0.804	0.806	0.791	0.782	0.780
$\overline{V}_a\,(m/s)$	0.496	0.555	0.596	0.580	0.565

Table 5.5 Minimum velocities at different elevations above the channel bed, before and after the entrance to the expansion for FB4.

h(m)	0.230	0.200	0.150	0.100	0.050
$V_{\min,b}\,(m/s)$	0.203	0.564	0.558	0.547	0.544
$V_{\min,a}\,(m/s)$	0.005	0.007	0.009	0.003	0.003

Table 5.6 Percentage in area of eddies at different elevations above the channel bed, in the expansion and downstream of the expansion for Run FB4.

h(m)	0.230	0.200	0.150	0.100	0.050
E_{ex} (%)	10.6	9.5	3.9	5.6	4.5
$E_{d/s}$ (%)	4.5	1.7	1.9	1.8	1.6

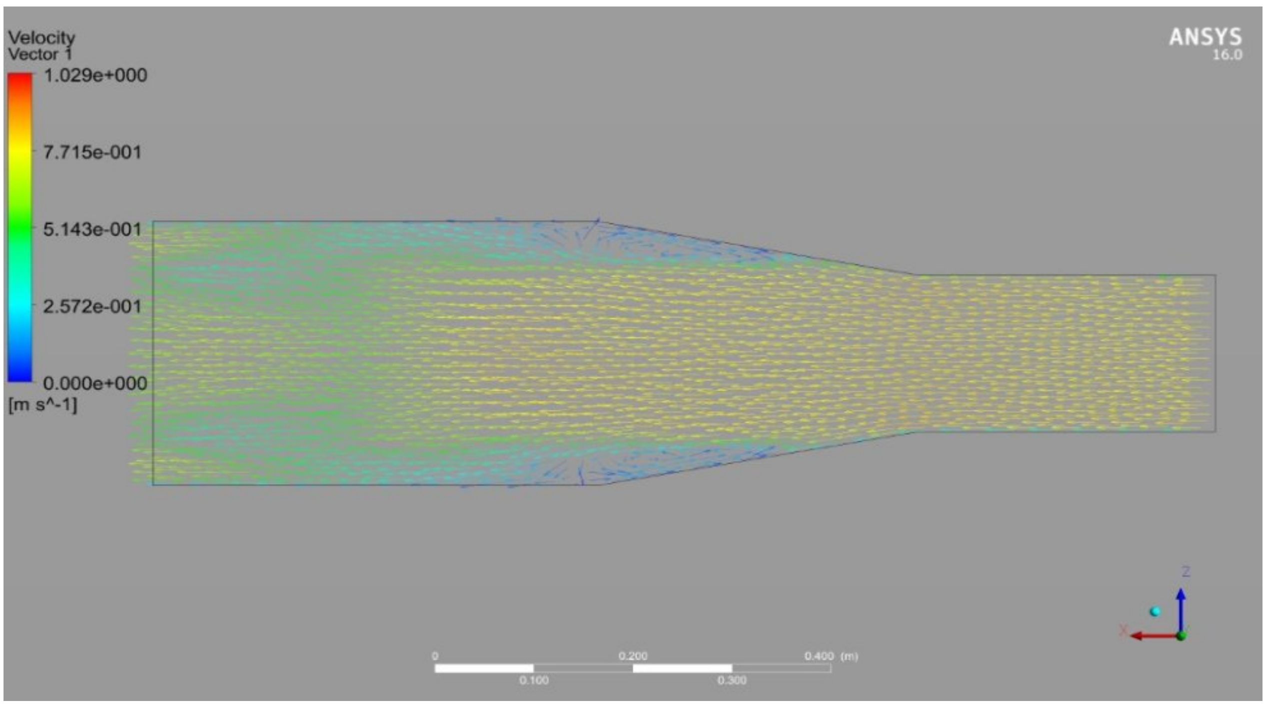
Table 5.7 Percentage in area of eddies near the right and left sidewalls in the expansion for Run FB4.

h(m)	0.230	0.200	0.150	0.100	0.050
E_r (%)	15.1	16.4	6.8	9.9	7.6
E_l (%)	5.1	2.5	0.2	0.2	0.08

Figure 5.3 shows the velocity vectors for Run FB4 at an elevation of 0.200 m above the channel bed. The area occupied by eddies to the left is negligible below 0.230 and the area to the right reduces at elevations below the surface.

5.3.1 The effects of a hump

The effects of a hump on flow velocity and eddies are revealed through Runs HQ1 and HH1. The presence of a hump tends to increase the flow velocity and reduce eddy motions. The simulation conditions with a hump for α 10.34° are given in Table 5.1, where HQ1 refers to a 1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) hump, and HH1 refers to a 1/3'' (or 0.00838 m, with $\Delta z / y$ 3.35%) hump At an elevation of *h=0.200 m,* we compare the velocity field and eddy motion area for Runs FB4, HQ1and HH1.In Table 5.8 the average and minimum velocities before and after the entrance to the expansion for FB4, HQ1, and HH1are listed.



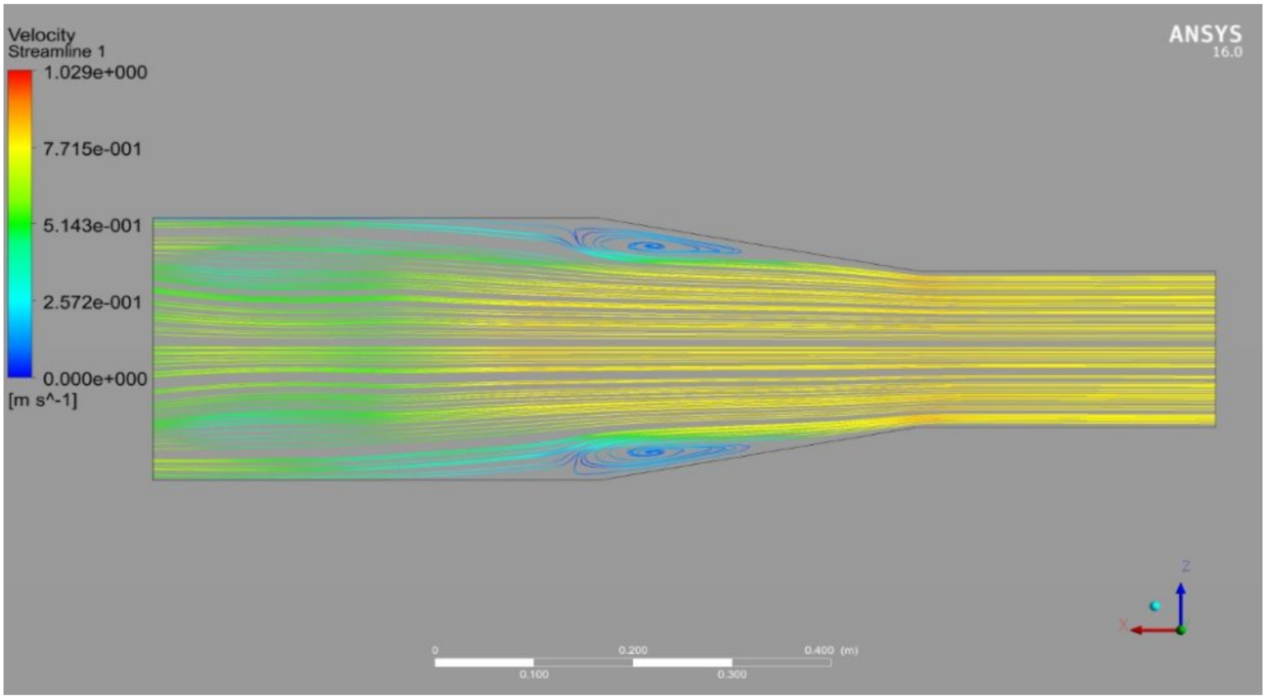


Figure 5.3 Velocity vectors in the expansion at an elevation of 0.200 m above the channel bed for Run FB4. The Froude number is 0.5. The maximum velocity is 0.89m/s.

Table 5.8 Average and minimum velocities before and after the entrance to the expansion for a flat-bottom expansion, and expansions with a hump. The elevation is 0.200 m above channel bed.

Runs	FB4	HQ1	HH1
$\overline{V}_b\,(m/s)$	0.805	0.772	0.807
$\overline{V}_a\,(m/s)$	0.555	0.530	0.571
$V_{\min,b}\,(m/s)$	0.564	0.132	0.390
$V_{\min,a}\,(m/s)$	0.007	0.001	0.088

It is observed that the use of a 1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) hump, (HQ1), does not have a considerable effect on the average and minimum velocities; however, the use of 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%) hump, (HH1), increases the average and minimum velocities after the entrance to the expansion.

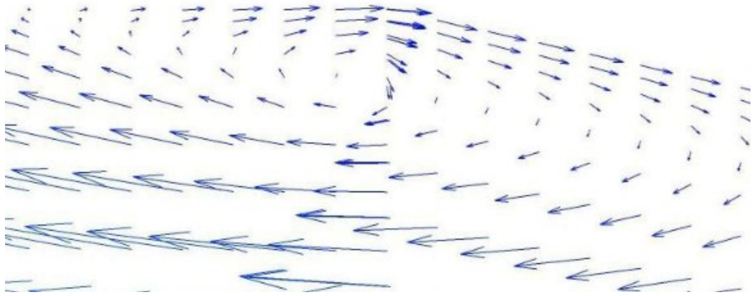
In Table 5.9, we compare the percentage in area of eddies for a flat-bottom channel and channels with a hump at an elevation of 0.200 m above the channel bed. It is observed that the

1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) hump, has reduced the percentage of eddies in the expansion area from 9.5% to 7.8%. The use of the 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%) hump reduces the percentage to a negligible value of 0.5%. Similar trends are observed for percentages to the right sidewall of the channel expansion. The percentage of eddies in the downstream region is small and remains almost the same for channels without and with a hump.

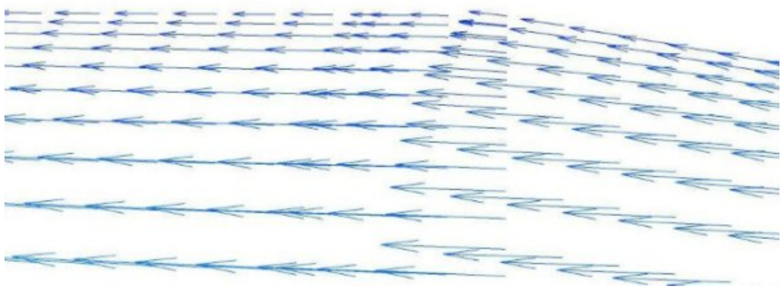
In Figure 5.4 we show the velocity vectors for a flat bottom channel (panel a) and a channel with a 1/2" (or 0.0127 m) hump (panel b), around the exit of the expansion. The region of

Table 5.9 Percentage in area of eddies in the expansion and between the downstream end of the expansion and downstream of the model channel for a flat-bottom expansion, and expansions with a hump. The elevation from channel bed is 0.200 m.

Runs	FB4	HQ1	HH1
E_{ex} (%)	9.5	7.8	0.5
E_r (%)	16.4	12.2	0.5
E_l (%)	2.5	3.4	0.4
$E_{d/s}$ (%)	1.7	2.0	1.8



(a)



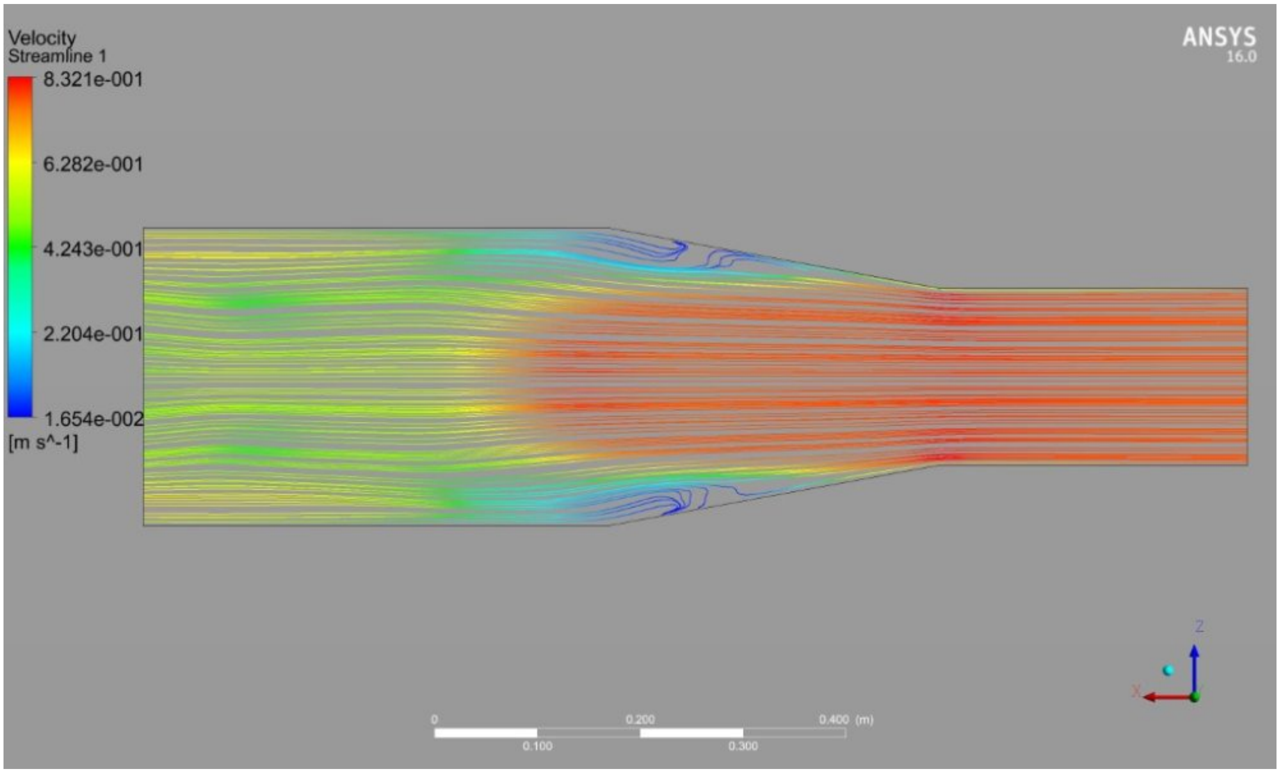
(b)

Figure 5.4 A comparison of velocity vector around the exit of the expansion between a flat bottom channel (a) and a channel with a 1/3" (0.0083 m) hump (b). The elevation is 0.200 m above the channel bed.

eddies (flow separation area) to the right is clearly present for Run FB4, and almost vanishes for Run HH1. Similar behaviours are observed at other elevations above the channel bed.

Figure 5.5 shows the velocity streamlines for Runs FB4 and HH1 at an elevation of 0.200 m above the channel bed. The presence of eddies (flow separation) to the right for Run FB4 (panel a) is clearly shown. The effect of the hump on reducing the eddy area is clearly observed in panel (b).

(a)



(b)

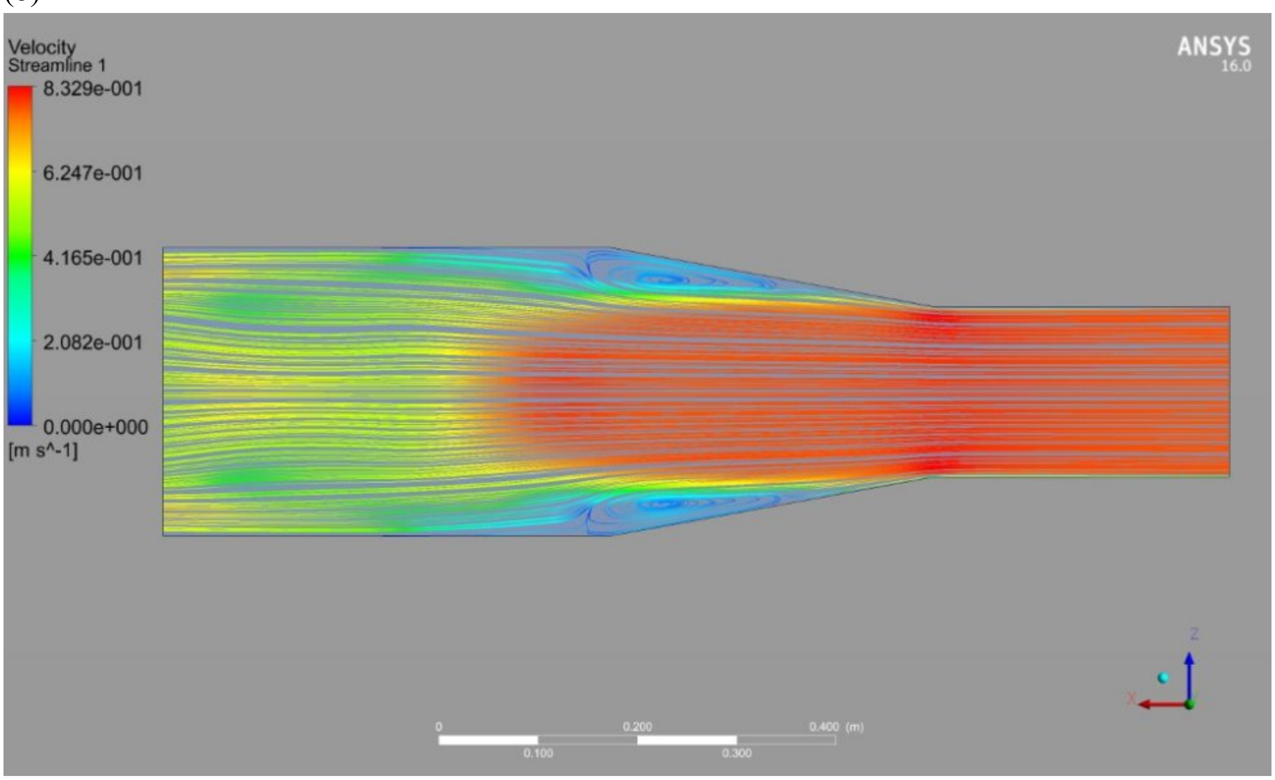


Figure 5.5 Velocity streamlines at an elevation of 0.200 m above the channel bed for Runs FB4 and HH1. The Froude number is 0.5.

5.4 Velocity field and flow separation for α 7.54° and F_r 0.5

In this section we compare results of the velocity field for expansions with a divergence angle of 7.54º (FB5, HQ2, and HH2 in Table 5.1). Using a smaller angle of divergence (FB5 in table 5.1), we carried out model runs for a flat bottom expansion and expansions with a hump. The angles and other parameters of the different expansions are given in Table 5.1. For α 7.54°, FB5 is for a flat bottom expansion and HQ2 and HH2 are for expansions with 1/4" (or 0.00635 m), and 1/3"(or 0.00838 m), respectively.

The results of Run FB5 show the same features as for Run FB4. However, due to the use of a smaller angle of divergence, eddies are reduced and the velocity vectors are more uniform, i.e. the difference between the average velocity before and after the entrance to the expansion decreases. Tables 5.10 and 5.11 show the average and minimum velocities for Run FB5. In Table 5.11, the minimum velocities after the entrance to the expansion are close to zero, which confirms the presence of eddies. To show the effects of the angle of divergence on velocity drop after the entrance to the expansion, we compare the velocity drops for Runs FB4 and FB5. The velocity drop is defined as the absolute value of the difference between the average velocities before and after the entrance to the expansion.

Table 5.10 Average velocities at different elevations above the channel bed, before and after the entrance to the expansion for Run FB5.

Elevation(m)	0.230	0.200	0.150	0.100	0.050
$\overline{V}_b (m/s)$	0.765	0.763	0.759	0.759	0.754
$\overline{V}_a (m/s)$	0.512	0.592	0.602	0.613	0.608

Table 5.11 Minimum velocities at different elevations above the channel bed, before and after the entrance to the expansion for Run FB5.

Elevation(m)	0.230	0.200	0.150	0.100	0.050
$V_{\min,b}\ (m/s)$	0.121	0.152	0.155	0.148	0.144
$V_{\min,a}\ (m/s)$	0.009	0.004	0.002	0.007	0.005

Table 5.12 shows the velocity drops for Runs FB4 and FB5 at different elevations above the channel bed. Smaller velocity drops are observed for Run FB5 which indicates more uniformity for water velocity before and after the entrance to the expansion.

Table 5.12 A comparison of velocity drops between Runs FB4 and FB5.

Elevation(m)	0.230	0.200	0.150	0.100	0.050
Velocity drop for FB4 (m/s)	0.308	0.250	0.195	0.202	0.216
Velocity drop for FB5 (m/s)	0.253	0.171	0.157	0.146	0.146

Table 5.13 shows the area occupied by eddies in the expansion region and the area occupied by eddies downstream of the expansion (i.e. between the exit of the expansion and the downstream end of the model channel). The area occupied by eddies increases with increasing elevation. As given in Table 5.13 and Table 5.6, the results for FB4 show that the area of eddy motions reduces for smaller angles of divergence. The region of eddies in downstream is similar between Runs FB4 and FB5. The results for Run FB5show less flow separation and hence less energy losses, however, the drawback of using small angles of divergence is the increase in length of the expansion, which is not an economic solution.

Table 5.14 shows the area of eddy motions to the right and the left, respectively. The asymmetric behaviour of eddy motions is clear; no eddy motions are observed to the left sidewall, whereas eddy motions are present to the right.

Table 5.13 Percentage in area of eddies at different elevations above the channel bed, in the expansion and downstream for Run FB5.

Elevation(m)	0.230	0.200	0.150	0.100	0.050
E_{ex} (%)	8.2	3.3	3.7	1.9	1.0
$E_{d/s}$ (%)	3.5	2.2	1.9	2.2	1.6

Table 5.14 Percentage in area of eddies near the right and left sidewalls in the expansion for Run FB5.

Elevation(m)	0.230	0.200	0.150	0.100	0.050
E_r (%)	16.5	6.6	7.4	3.6	2.0
E_l (%)	0.0	0.0	0.0	0.0	0.0

5.4.1 The effects of a hump

The effects of a hump on velocity vectors and eddies are evaluated through Runs HQ2 and HH2 at an elevation of 0.230 m above the channel bed. The average and minimum velocities before and after the entrance to the expansion are listed in Table 5.15. The use of a 1/4″(or 0.00635 m, with $\Delta z / y$ 2.54%)hump,(HQ2), does not have a considerable effect on the average and minimum velocities, however, the use of 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%) hump, (HH2), increases the average and minimum velocities after the entrance to the expansion. The minimum velocity before the entrance to the expansion is considerably increased in Run HH2. This is a decrease in the eddy motions right before the entrance to the expansion.

In Table 5.16 the percentage in area of eddies for a flat-bottom channel and channels with a hump are compared .The elevation is 0.230 m above the channel bed. The 1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) hump, has reduced the percentage in area of eddies in the expansion from 8.2% to 4.3%. The 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%) hump reduces the percentage to a considerably smaller value of 1.4%. Similar trends are observed for percentages to the right of the channel expansion. Note that due to the use of a smaller angle of divergence, the expansion is more gradual. Thus, the asymmetric behaviour of eddies is more clear, where in Table 5.16 it is observed that the eddy percentage to the left is zero, even for a flat bottom expansion.

The eddy motions are persistent over a long distance downstream of the expansion. Therefore, the eddies are observed even after the expansion (the last row of Table 5.16). The percentage in area of eddies in the downstream region is small for expansions without and with a hump, however, the percentage in area occupied by eddies decreases when a hump is used.

Table 5.15 Average and minimum velocities before and after the entrance to the expansion for a flat-bottom channel (FB5) and channels with a hump. The elevation above the channel bed is 0.230 m.

Runs	FB5	HQ2	HH2
$\overline{V}_b\,(m/s)$	0.765	0.766	0.793
$\overline{V}_a\,(m/s)$	0.512	0.571	0.582
$V_{\min,b}\ (m/s)$	0.121	0.118	0.236
$V_{\min,a}\ (m/s)$	0.009	0.008	0.033

Table 5.16 Percentage in area of eddies in the expansion and between the downstream end of the expansion and downstream end of the model channel for flat-bottom channel (FB5) and channels with a hump. The elevation above the channel bed is 0.230 m.

Runs	FB5	HQ2	HH2
E_{ex} (%)	8.2	4.3	1.4
E_r (%)	16.5	8.8	2.6
E_l (%)	0.0	0.0	0.0
$E_{d/s}$ (%)	3.5	2.0	1.4

5.5 Velocity field and flow separation for α 5.04° and F_r 0.5

In this section we compare the results of the velocity field for expansions with a divergence angle of 5.04 ° for Runs FB6, HQ3, and HH3 (See Table 5.1). For α 5.04°, the results for a flat-bottom expansion (FB6) and expansions with a hump (HQ3, and HH3) are similar to the results for previous Runs with larger angles. Due to the use of a small angle of divergence, compared to Runs FB4 and FB5, the percentage in area of eddies considerably drop in case of FB6. Tables 5.17 and 5.18 compare the velocity field and flow separation for Runs FB6, HQ3, and HH3.The elevation is 0.200 m above the channel bed. The results for all the expansions confirm that a hump, especially a 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%) hump have significant effects on reducing eddy motions and hence eddy areas and on increasing flow velocities after the entrance to the expansion. Although the area percentages are small even for the case of FB6, the use of a hump (especially a 1/3'' hump) will reduce these percentages to a negligible level.

Table 5.17 Average and minimum velocities before and after the entrance to the expansion for a flat-bottom expansion (FB6), and expansions with a hump (HQ3 and HH3). The elevation above the channel bed is 0.200 m.

Runs	FB6	HQ3	HH3
$\overline{V}_b\,(m/s)$	0.772	0.769	0.774
$\overline{V}_a\,(m/s)$	0.585	0.594	0.602
$V_{\min,b}\,(m/s)$	0.179	0.183	0.324
$V_{\min,a}\,(m/s)$	0.063	0.090	0.120

Table5.18 Percentage in area of eddies in the expansion and between the downstream end of the expansion and downstream of the model channel for a flat-bottom expansion (FB6), and expansions with a hump (HQ3and HH3). The elevation above the channel bed is 0.200 m.

Runs	FB6	HQ3	HH3
E_{ex}(%)	1.1	0.7	0.2
E_r (%)	2.0	1.4	0.4
E_l (%)	0.0	0.0	0.0
$E_{d/s}$ (%)	0.1	0.7	0.3

5.6 Velocity field at different Froude numbers

The effects of an expansion on creating eddies and the effects of a hump on reducing eddy motions are the most profound for a large angle of divergence (α 10.34°), we use this angle in

Runs FB4, HQ1, and HH1 in order to study the effects of different Froude numbers. The purpose is to show how the percentage in area of eddies changes with the Froude number. We consider different humps at different Froude numbers, i.e. to what extent the humps will reduce the percentage in area of eddies.

For Runs FB4, HQ1and HH1 (Table 5.1), the Froude number ranges from Fr = 0.3 to 0.7. In addition to varying the Froude number, the downstream elevation of water above the channel bed has changed to 0.257 m for the Froude number F_r 0.3 and 0.291 m for F_r 0.7 .

At the inlet, velocity is 0.47 m/s for Froude number F_r 0.3 , and 1.1 m/s in corresponded to the Froude number F_r 0.7 . At smaller inlet velocities, smaller regions Of separating waves and eddies are expected. Therefore, we expect to observe less eddies at smaller Froude numbers. Tables 5.19 shows the percentage in area of eddies for a flat bottom channel (FB4) at the Froude number F_r 0.3 . A Comparison of the results given in Table 5.19 with the results in Table 5.6 (for FB4 at the Froude number F_r 0.5) shows a considerable reduction in eddy motions in the expansion.

Table 5.19 Percentage in area of eddies at different elevations above the channel bed, in the expansion and downstream for Run FB4 at the Froude number F_r 0.3 .

Elevation(m)	0.230	0.200	0.150	0.100	0.050
E_{ex} (%)	3.8	4.9	4.0	5.4	3.0
$E_{d/s}$ (%)	3.3	2.5	2.7	2.6	5.0

The effects of a hump on decreasing the eddy area are summarised in Table 5.20. The use of a 1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) hump helps reduce the eddy motion area in the expansion. The use of a 1/3″ (or 0.00838 m, with $\Delta z / y$ 3.35%) hump has a considerably better effect, where the area of eddies in the expansion has reduced to a negligible value of 1.2%. Figure 5.6 shows that, for large Froude numbers (i.e. F_r 0.7), the eddies appear in almost all the regions of the expansion, beginning from the area before the entrance to the expansion. The percentage in area of eddies is larger at elevations closer to the water surface (Table 5.21). Therefore, the flow is more turbulent closer to the surface, with larger areas of eddies. A comparison among Table 5.21 with Tables 5.19 and 5.6, indicates that the area of eddies inside the expansion considerably increases at the Froude number F_r 0.7 .

Table 5.22 compares effect of 1/4” (or 0.00635 m), and 1/3" (or 0.00838 m) humps on the eddy motion areas for Froude number of 0.7, at elevation of 0.200 m above the channel bed. As observed, HQ1 does not have a constructive effect; however, the 1/3" (or 0.00838 m) hump, i.e. HH1, considerably reduces the area of eddy motions and completely vanishes this area in the left sidewall.

Table 5.20 Percentage in area of eddies in the expansion and between the downstream end of the expansion and downstream of the model channel for a flat-bottom expansion, and expansions with a hump. The Froude number is 0.3. The elevation above the channel bed is 0.200 m.

Runs	FB4	HQ1	HH1
E_{ex} (%)	3.8	3.0	1.2
E_r (%)	7.6	5.9	2.4
E_l (%)	0.0	0.0	0.0
$E_{d/s}$ (%)	3.3	2.9	1.7

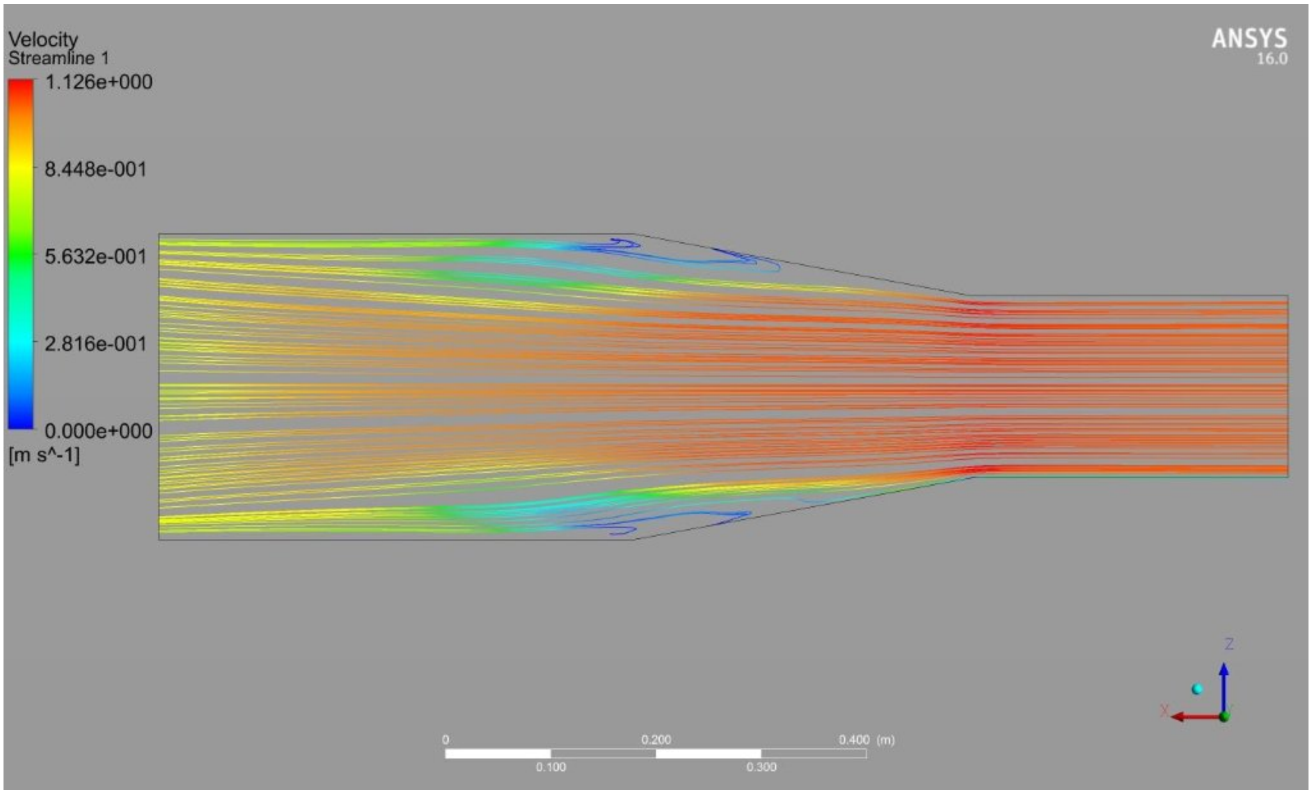


Figure 5.6 Velocity streamlines at an elevation of 0.230 m above the channel bed for Run FB4. The Froude number is 0.7.

Table5.21 Percentage in area of eddies at different elevations above the channel bed, in the expansion and downstream for Run FB4 .The Froude number is 0.7.

Elevation(m)	0.230	0.200	0.150	0.100	0.050
E_{ex}(%)	27.5	20.5	3.1	2.8	5.3
$E_{d/s}$ (%)	7.5	9.3	3.5	5.5	4.5

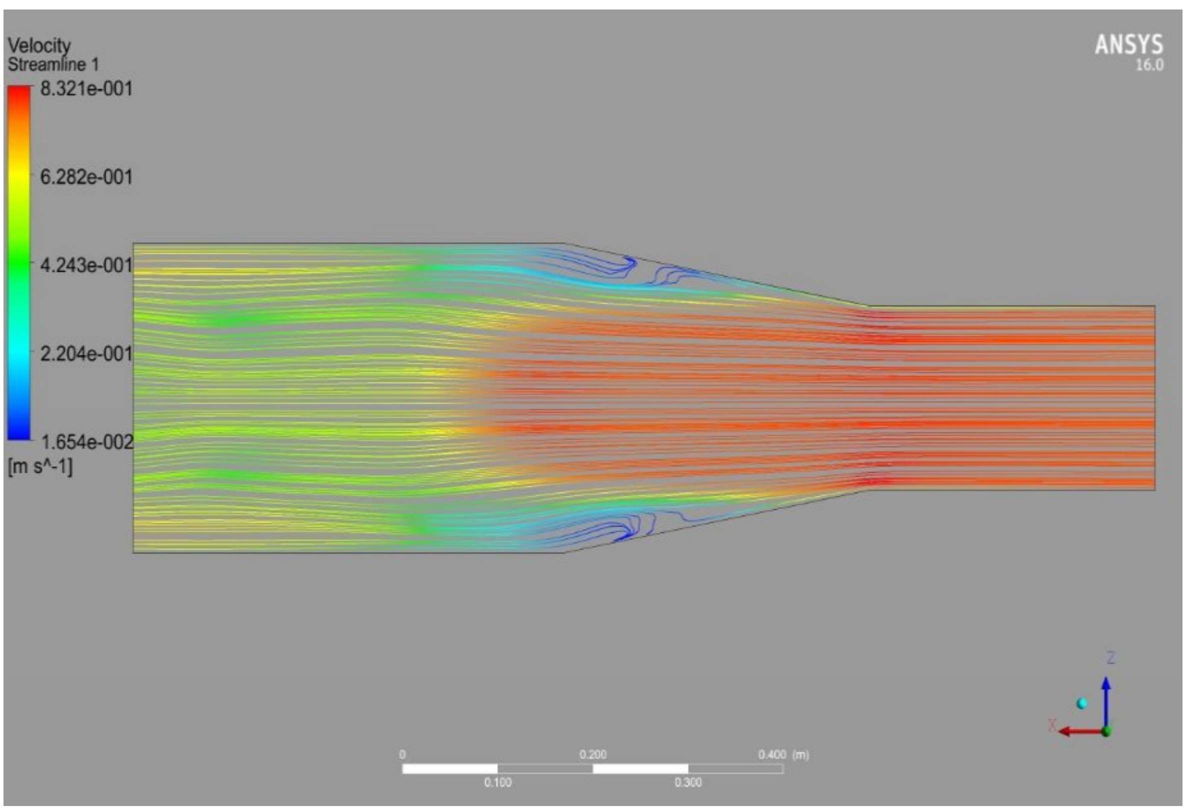
Table 5.22 Percentage in area of eddies in the expansion and between the downstream end of the expansion and downstream of the model channel for a flat-bottom expansion,

and expansions with a hump. The Froude number is 0.7. The elevation above the channel bed is 0.200 m.

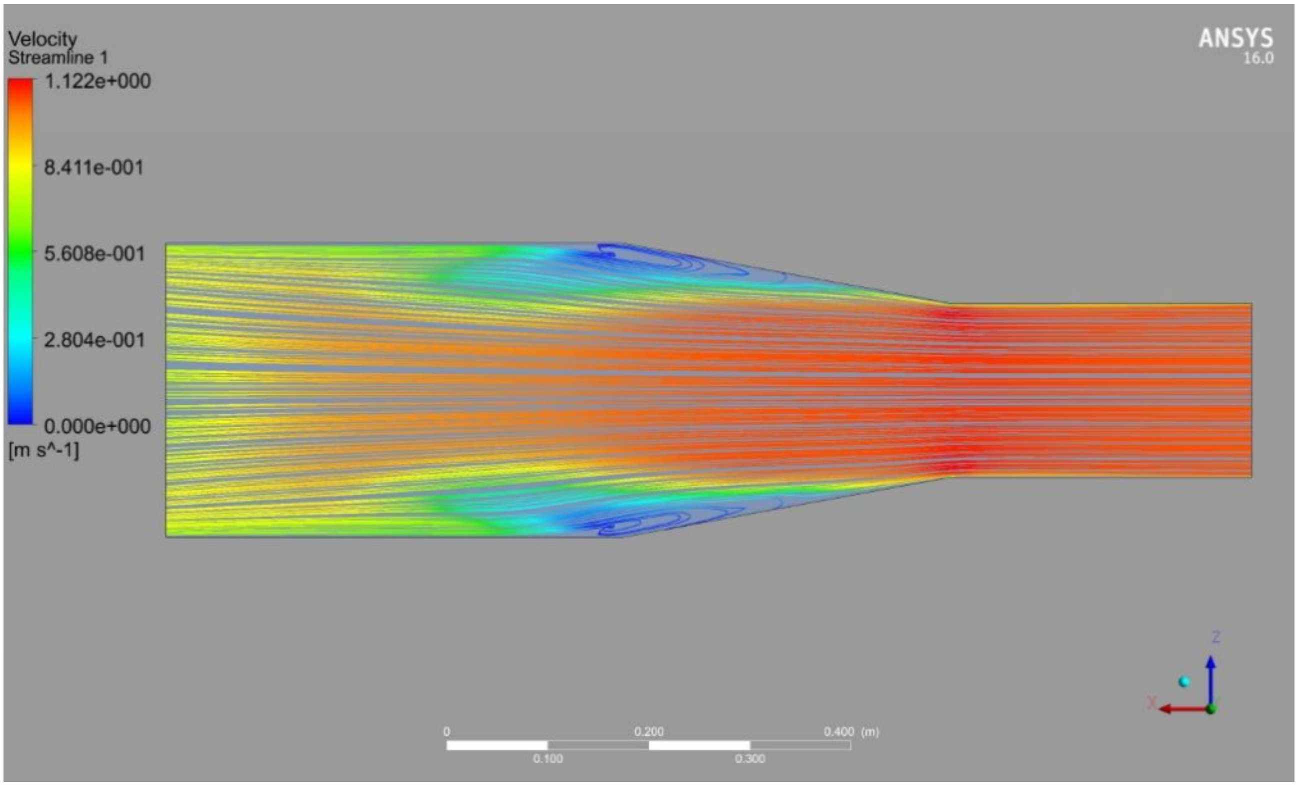
Runs	FB4	HQ1	HH1
E_{ex}(%)	20.5	28.7	6.8
E_r(%)	28.3	32.0	12.6
E_l(%)	13.9	22.3	0.0
$E_{d/s}$ (%)	9.3	3.3	3.7

Figure 5.7 shows the effect of 1/3" (or 0.00838 m, with $\Delta z / y$ 3.35%) hump in reducing

eddies at elevation of 0.200 m above the channel bed. Also by comparing Figure 5.7 with Figure 5.6, it is obvious that the region of eddies becomes smaller at lower elevations.



(a)



(b)

Figure 5.7 Velocity streamlines at an elevation of 0.200 m above the channel bed for Runs FB4 (panel a) and HH1 (panel b). The Froude number is 0.7.

5.7 The effects of the Froude numbers

In this section we determine velocity contours at different cross-sections along the channel expansion, when the angle of divergence is α 10.34° and the Froude number varies from 0.3 to 0.7. Figure 5.8 shows the percentage in area of backward flow for a flat-bottom expansion (FB4) when the Froude number changes from 0.3 to 0.7. The percentage of backward flow increases at higher Froude numbers, as expected. At higher Froude numbers, the flow is stronger and flow separation in the expansion is more likely to occur

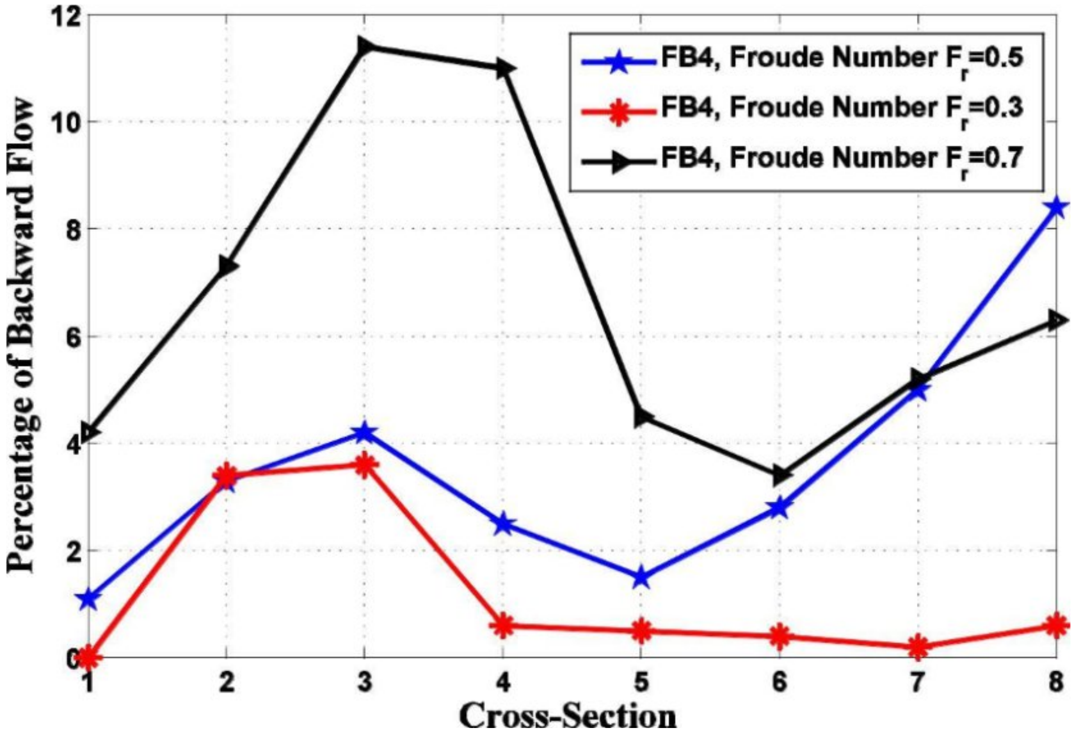


Figure 5.8 Percentage in area of backward flow at different cross sections for a flat-bottom expansion (FB4), at different Froude numbers

Generally speaking, the percentage in area of backward flow at the Froude number .F_r 0.3 is small, even in a flat-bottom expansion (see Figure 5.9). Therefore, it is not expected to observe considerable changes in this percentage when using humps. However, based on our observations, humps help reduce the percentage of backward flow at some cross-sections. The effects of a hump on changing the percentage of backward flow at the Froude number F_r 0.7 are shown in Figure 5.9. The 1/4″ (or 0.00635 m, with Δz / y 2.54%) hump has maintained similar percentages for most cross-sections and has successfully reduced the percentage of backward flow in the middle of the expansion . The 1/3″ (or 0.00838 m, with Δz / y 3.35%) hump has reduced the percentage of backward flow from the beginning up to the middle of the expansion, however, it has increased the percentage at some cross-sections after the middle of the expansion. In general, based on Figure 5.9, we cannot recommend a 1/3″ (or 0.00838 m, with Δz / y 3.35%) hump as a solution to reduce the percentage of backward flow at the Froude number F_r 0.7 .

At the exit of the expansion, is one of the cross-sections where the 1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) hump has reduced the percentage of backward flow, compared to a flat-bottom expansion (FB4). These effects are clearly shown by comparing velocity contour for Run FB4 and velocity contours for Run HQ1 at Cross-section 8. The effects of a 1/4″ (or 0.00635 m, with $\Delta z / y$ 2.54%) hump on reducing the backward flows (red region) are shown, especially next to the sidewalls, and next to the bottom corner

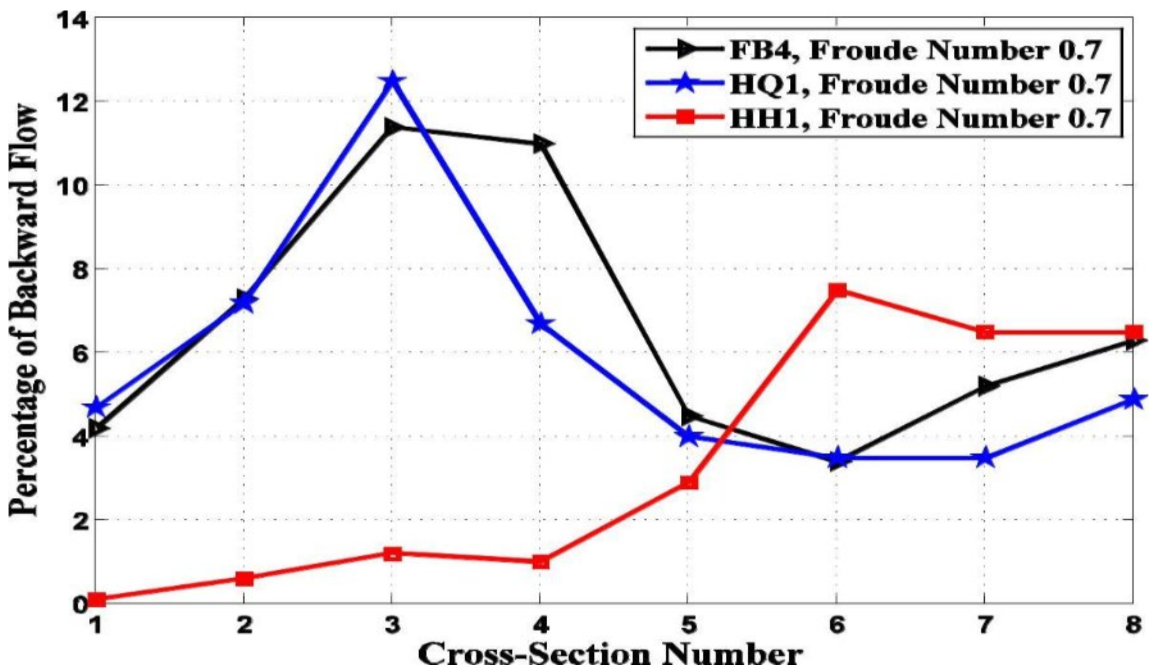


Figure 5.9 Percentage in area of backward flow at different cross-sections for a flat-bottom expansion (FB4), and expansions with a hump (HQ1 and HH1).

Chapter Six

Discussions and Conclusion

6.1 Discussions

This study deals with the issue of flow separation, energy losses and eddy motions in flows through open-channel expansions, which is important. In hydraulic engineering systems such as irrigation networks and hydropower structures, expansions are useful for providing a necessary cross-sectional increase in the direction of flow. However, energy losses in expansions are undesirable from the perspective of energy conservation and possibly expansion-induced turbulent eddy motions must be controlled to prevent the hydraulic engineering systems from damage. This modelling study has made a number of contributions, including

(1) an improved understanding of the behaviour of subcritical flows in expansions, e.g. variations in flow streamlines, velocities and eddy structures;

(2) a successful extension of experimental results to cover a wide range of conditions in terms of the angle of divergence, bottom geometry and the Froude number;

(3) quantitative evaluations of the effectiveness of altering the bottom geometry in the suppression of flow separation and eddy motions.

These contributions have been made through CFD simulations of three-dimensional subcritical turbulent flows in channel expansions with or without a hump fitted at the channel bed. These simulations have produced steady state solutions of the flow field for given hydraulic conditions and channel geometry. We have ensured that the model solutions are independent of mesh resolutions and configurations, and are not subject to artificial end effects. The k-ω turbulence model was used for turbulence closure in the simulations, which is known to handle anticipated anisotropic turbulence well.

Comparisons of the velocity field, vorticity structure and flow reversal in the expansion between the cases with and without a hump have clearly revealed the effects of using humps on the control of flow separation and eddy motions. Sudden expansions are easy and presumably less expensive to build, but they are known to cause flow separation and contribute to the formation of turbulent eddies. Therefore, they are not hydraulically efficient. Previously, research efforts have been made to improve the hydraulic efficiency; the focus has been on optimising expansion's shapes in the horizontal, but their research efforts have not produced consistent results (see e.g. Hinds, 1927; Smith and Yu, 1966; Swamee and Basak, 1992).

This modelling study represents an extension to the interesting idea of making modifications to the expansion geometry in the vertical, which arguably would be easier and less expensive, compared to modifications to the expansion sidewalls. It is possible to incorporate a simple hump at the channel bed to achieve smooth water surface and flow profiles in expansions and hence to reduce flow energy losses there and further downstream. Thus, the results from this study have important implications to the design of hydraulically efficient channel expansions. Within the regime of subcritical flow, the actual values for the Froude number should be taken into account in the design; this is among the new findings from this study.

The modelling strategies followed in this modelling study are appropriate, and the results are relevant, supported by reasonable comparisons with experimental data (for a limited number of cases) as well as with theoretical results (available for some simplified conditions). The comparisons are in terms of a dimensionless energy loss coefficient for channel expansions. The modelling strategies have allowed efficient and systematic explorations of combinations of different expansion geometry, flow conditions and hump configurations.

6.2 Conclusion

In total, 19 model runs were carried out in this study for predictions of the flow field in channel expansions with or without a hump fitted at the channel bed. These model runs covered conditions of the angle of divergence α = 5.04, 7.54 and 10.34, and the Froude numbers Fr = 0.3, 0.5 and 0.7. From the model results, we determined the percentage in area occupied by eddies, the percentage in area where the flow reverses direction, and the percentage in area where the vorticity is high. We have validated the modelling methodologies by achieving good comparisons with experimental data. Distributions of three-dimensional water velocities, vorticity contours, and along-channel velocity contours at selected vertical and horizontal planes for the cases of with and without a hump are presented. An analysis of the model results has leaded to the following conclusions:

(1) When the angle of divergence reaches α = 7.54°, flow separation from the expansion sidewalls occurs in the expansion and persistent eddy motions take place not only locally in the expansion but also cover a long distance further downstream. The flow patterns and eddy motions are asymmetric about the expansion's centreline, although the expansion geometry is symmetric about the centreline. Also, there are significant variations in the velocity field with height above the channel bed.

(2) When α reaches 10.34°, intensive flow separation and eddy motions occur. The resultant energy losses are significant, with the energy loss coefficient being as large as 0.42 (for *Fr* = 0.5, see Tables 5.1 and 5.32) and 0.74 (*Fr* = 0.7). An erosion problem is expected if the expansion is built with erodible materials.

(3) At moderate Froude numbers ($Fr \leq 0.5$), the use of a 1/3″(or 0.00838 m, with $\Delta z / y$ 3.35%)hump, which is about 5% of the depth of flow imposed at the entrance of

a gradual channel expansion, suffices to suppress flow separation from the expansion sidewalls and eliminates almost completely flow reversal and expansion-induced flow energy losses. The energy loss coefficient is reduced from 0.42 to 0.09. With respect to the elimination of flow reversal, both a 1/3″(or 0.00838 m, with $\Delta z / y \quad 3.35\%$) hump and a 1/4″(or 0.00635 m, with $\Delta z / y \quad 2.54\%$) hump are very effective.

(4) At high Froude numbers ($Fr \quad 0.7$), the use of a 1/3″ hump (with $\Delta z / y \quad 3.35\%$) has limited effects of on the control of flow separation and energy losses, with the energy loss coefficient dropped from 0.74 to 0.53. The significance of this finding is that the design of hydraulically efficient needs to consider the actual Fr values.

(5) The angle of divergence of the expansion in question is an influential factor in the hydraulic performance of humps. When the angle of divergence does not exceed 5.04°, there are no significant flow separation and eddy motions, and therefore the use of a hump may be redundant.

(6) When the angle of divergence and the Froude number are large (α = 10.34º and Fr = 0.7), the use of a 1/3″(or 0.00838 m, with $\Delta z / y \quad 3.35\%$) hump is shown to reduce the region in the expansion of high vorticity (defined as vorticity higher than 9.0 s^{-1}) by about 50%. In terms of flow reversal control, the use of a 1/3″(or 0.00838 m, with $\Delta z / y \quad 3.35\%$) hump or a 1/4″(or 0.00635 m, with $\Delta z / y \quad 2.54\%$) hump works at some vertical cross sections bur does not at others.

The use of a hump is shown to force flow to accelerate, and as a result, the otherwise adverse pressure gradient, which is known to be responsible for flow separation, diminishes. A hump in the vertical can easily be incorporated into the bed of existent channel expansions, and would be less expensive to construct than to modify the horizontal shape (or the sidewalls) of existent expansions. The results presented in this study are of practical values for the optimal design of humps.

6.3 Suggestions for Future Research

This study has limited to the case of expansions of rectangular cross section. Future research on the topic should consider expansions of other shapes (e.g. trapezoidal shape). This study should be extended to include more cases where the Froude number is high (Fr > 0.5). We have considered humps with a triangle profile. It is worthy a while to investigate whether or not humps with a smooth profile will lead to a substantially better performance. The combined numerical and experimental approach would be interesting to take to tackle the problem. Future research should remove the assumption that the approach flow is uniform.

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