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The effect of a difference in angle in two lateral inflow channels on the main channel's velocity

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Abstract
In this study, we examined the flow from two lateral inflow channels in a man-made open rectangular channel of an incompressible Newtonian fluid. The influences of the angles as it varies directly proportional to each other for two lateral inflow channels from zero to ninety degrees on how they affect the flow rate in the main rectangular open channel, were considered. When the flow rate increases, the discharge increases as well and a decrease in the flow velocity means a decrease in the discharge, because the discharge is directly proportional to the flow velocity. The flow-regulating equations are the continuity and momentum equations of movements that are extremely nonlinear and cannot be solved by an exact method. The method of finite difference is then used to numerically compute an approximate solution to these partial differential equations. Due to its precision, consistency, stability and convergence, these equations are solved using the finite difference method. MATLAB software used to generate the results which are analyzed using graphs. The analysis found that inclined lateral inflow channels at 45^0 increase the main channel's flow velocity more than 60^0 and 72^0, while 90^0 maintains the main channel's flow velocity constant.

Keywords: Lateral inflow, lateral angle, main channel

List of notations
v: Mean velocity of flow (m/s)
L: Length of the lateral inflow channel (m)
g: Acceleration due to gravity (ms^{-2})
Q: Discharge in the main channel (m^3s^{-1})
Q_1 and Q_2: Discharge of the lateral inflow channels (m^3s^{-1})
A: Flow's cross-sectional area (m^2)
n: The roughness manning coefficient ($Sm^{-1/3}$)
S_o: The channel's bottom slope
S_f: Friction slope $= \frac{n^2v^2}{R^{\frac{4}{3}}}$
T: Top width of free surface (m)
y: Depth of flow (m)
t: Time (s)
q: Lateral uniform inflow (m^2s^{-1})
R: Hydraulic radius (m)
x: Distance along the main flow direction (m)
θ_1 and θ_2: Angle of lateral discharge channel in degrees
Δ: forward difference
$\frac{\partial A}{\partial t}$: Rate of change in area of flow with time (m^2/s)
$\frac{\partial v}{\partial x}$: The rate at which the flow's mean velocity changes with distance (m/s)
$\frac{\partial y}{\partial x}$: Rate of change of depth of flow with distance (m/s^2)
$\frac{\partial Q}{\partial x}$: Rate of change in discharge with distance (m^2/s)
T_3: Top width of the main channel (m)
T_1 & T_2: Top width of the two lateral inflow channels (m)
c: Resistance coefficient of flow (Chezy coefficient)

Introduction

In 2018, 2019 and 2020, Kenya experienced heavy rainfall, resulting in bridges being swept away as rivers flooded and dams shattered its walls. Examples of this environmental disaster that occurred in 2018 are the Solai Dam in Nakuru, Kenya, which breached its walls and killed 47 people after it broke its walls and swept all people and everything in that village away. More so, in 2019 west Pokot land slide took place and roads were blocked and some bridges were swept away. In addition, Nakuru, Elgeyo Marakwet, Baringo, Nandi, Kisumu and many others are still affected by floods during normal rainfall. It is therefore very important to design channels that regulate such an environmental catastrophe and, more importantly, Use the same water to irrigate agricultural land. The fact that the flood problem still persists and the need to transport water for irrigation is still in demand means that an efficient channel model with two lateral inflows is needed to convey the maximum discharge. Perhaps there's a closed or open channel.

Open channels are known to be channels with an open top, while channels with a closed top are called closed channels. Good examples of open channels are rivers and streams while examples of closed conduits are pipes and tunnels. Open channels made of earth and concrete have been designed which have been of different cross-sections such as trapezoidal, rectangular and circular. In the world at large, engineers have attempted, among other things, to channel water to a specific location, Irrigation grids and dams for power generation are examples. In Kenya, most road networks lack efficient drainage systems, especially rural roads; hence, Road carnage, fatalities, and economic devastation are all too common, particularly when it rains. This has a negative effect on the achievement of Kenya's 2030 vision that aims to create a high-quality, internationally competitive and prosperous nation by 2030. There are three main pillars of the 2030 vision that the government aims to accomplish. These are foundations of economic, political and social value. These three pillars are connected to our research due to the fact that inadequate drainage directly affects people's economy. For example, transport is disrupted when it rains and roads are cut off by runoff, and this affects the flow of goods and services. Large amounts of cash are often used to repair bridges, sewers, airports and playgrounds. Due to the blockade of sewers and highways, people have also gone on strike and this affects the smooth running of businesses. In addition, Diseases outbreaks and other related health issues pose a danger to the population's health if drainage is insufficient. As a result, our study aims to find solutions to these drainage-related issues in order to contribute to the 2030 vision. The analysis would focus on appropriate angles to align with two inflow channels in order to aid in the prevention of drainage channel blockages, which are a frequent occurrence in drainage systems. We hope that the results of this study will be useful in the design of drainage systems for road production, sewer building, street drainage, long dams, and airport construction in Kenya and elsewhere.

Saint venant equation

It was developed by two mathematicians, De Saint venant and Bousinnesque, in the nineteenth century. From navier equation for shallow water flow condition and one dimension. Dynamic routing is the solution to the St. venant equation, and it is often used to measure or compare other techniques. In open channels, it is the equations that characterize the propagation of a flood wave in terms of distance along the channel and time. It is made up of two equations: the continuity equation and the momentum equation. The inertial terms appearing in the momentum equation of the Saint-Venant equations can be ignored for most flood events in most rivers because they are comparatively smaller than the terms arising from gravity and resistance forces Henderson (1963) [4], resulting in a simplified model of open channel flow. The shallow water wave propagation in open channels is represented by the Saint-Venant hydrodynamic equations, which are obtained from the depth-averaged Navier-Stokes equations. For a rectangular channel, the one-dimensional Saint-Venant equations are as follows (Chow 1959) [2]:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=0 \text{ Continuity equation (Conservation form)} \quad (1)$$

Momentum Equation (2)

$$\frac{1}{A}\frac{\partial Q}{\partial t}+\frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+g\frac{\partial y}{\partial x}-g(S_o-S_f)=0$$

Saint Venant suggested the above governing equations for one-dimensional unsteady flow in an open channel in 1871, which included continuity and momentum equations, and Shang *et al.* (2012) [11] accepted them.

Tuitoek and Hicks (2001) [14] investigated flood management by simulating compound channels with erratic flow in order to better manage floods. By developing a model based on the Saint Venant equations of flow, they added some terminology in order to account for the momentum phenomenon of move to integrate an inconsistency in the flow in the compound channels.

Kwanza *et al*. (2007) [6] studied the effects of lateral discharge and channel slope, width, velocity, and depth as they vary from one point in the channel to the next on fluid velocity and channel discharge in both trapezoidal and rectangular channels. They noted that in order to increase channel discharge, the channel's slope, width, and lateral discharge all need to be increased. Furthermore, by reducing the wetted perimeter, the fluid flow rate increased.

Fluid flow in open rectangular and triangular channels was studied by Thiong'o (2011) [12]. Her observations on rectangular channels were close to those of Kwanza *et al* (2007) [6]. In an open rectangular channel, the flow velocity increased as the slope, discharge, and width increased, according to their findings. Increases in the wetted periphery of the channel, on the other side, resulted in a decrease in flow velocity. They both used the finite difference method as a computational instrument to solve the continuity and momentum equations.

The main channel's ratio of downstream to upstream discharge, as defined by Ramamurthy and Satish (1988) [24], Ingle and Mahankal (1990) [18], is the most important parameter in evaluating open flow with a 90° lateral channel. When these results were compared to some experimental findings, it was discovered that the study yielded satisfactory results.

The flow structure is defined by the roughness of the bed, as well as the velocity ratio between the branch and main channels, according to Neary and Odgaard (1993) [23].

Barkdoll *et al.* (1999) discovered that the diversion flow ratio has the greatest impact on the lateral intake sediment diffusion ratio, and is done in a straight line with a 90^0 intake angle.

Yang *et al* (2009) [16] looked at flow systems of 90°, 45°, and 30° diversion angles. To boost the flow pattern of the fluid, a diversion angle of 30° to 45° was suggested.

For open channel flows with uniform and localized lateral inflow, Fan and Li (2005) [3] developed diffusive wave equations. In their formulation, they provided the continuity and momentum equations for an open channel with a lateral inflow channel intersecting the main open channel at a differing angle.

When focusing on the sub-critical flow regime, Ramamurthy and Satish (1988) [24] theoretically and experimentally investigated dividing flows with a submerged lateral branch. The researchers theoretically developed a model by relating discharge ratios and downstream-to-upstream depth to the upstream Froude number. Their findings revealed that the re-circulatory zone downstream of the junction causes a contraction in the channel section, causing the flow to change to supercritical flow. The discharge in the branch of the lateral channel can be calculated using Mizumura *et al.* (2003)'s [22] formula for super-critical overflowing rivers, which compared well with Mizumura *et al* (2005)'s [21] results.

Mohammed (2013) [9] studied how four different angles affect the discharge coefficient by using an oblique weir in the flow direction, in comparison to the side of the channel floor. 30°, 60°, 75°, and 90° were the four angles that changed depending on the direction of flow. The research discovered that the highest discharge was reached when the side weir was tilted at 30 degrees.

Masjedi and Taeedi (2011) [8] looked into the effects of intake angle on lateral intake discharge ratio with 180° bend in the laboratory. The tests were carried out with a range of Froude numbers and intake angles. At a 45° lateral intake angle, the discharge ratio improved in all locations of the 180° flume bend, according to the study.

Shamaa (2002) [20] solved open channel operation-type problems using the finite difference Preissmann implicit construct, built on the Saint Venant equations. The implicit finite difference method model showed less oscillation and more precision as compared to an explicit model.

The diffusive schemes of Preissmann and Lax, which are two separate numerical methods for Saint Venant equations numerical solution, were investigated by Akbari and Firoozi (2010) [1]. With the aim of better understanding the propagation process, these equations regulate the flood waves propagate in natural waterways. The results of the study indicated that hydraulic parameters play a significant role in these waves.

Chagas and Souza (2005) [17] used the study of floods in rivers to solve the Saint Venant equation. The aim of this analysis was to achieve a better understanding of the propagation process by using a discretization for the Saint Venant equations. According to their observations, hydraulic parameters play a significant part in the transmission of flood waves.

Karimi *et al*. (2014) [19] conducted research on fluid modeling in the case of a single inflow channel on an open channel, and discovered that the velocity of the main open channel does not necessarily increase as the angle of the lateral inflow channel is increased. Angles between 30 and 50 degrees produce higher velocity values in the main open channel than other angles.

In a statistical model of fluid flow in an open trapezoidal channel with lateral inflow channel, Samuel M.K. (2020) [10] found that decreasing the cross-sectional area increases flow velocity while increasing the length of the lateral inflow channel decreases flow velocity. It's also worth noting that increasing the lateral inflow channel's velocity increases the flow velocity, and that an angle of thirty to fifty degrees increased the flow velocity relative to other lateral inflow channel angles.

Mathematical model case

A mathematical model of an open rectangular channel with two angled lateral inflow channels. Q, q_1 and q_2 reflect the discharge into the rectangular open channel, as well as the two lateral inflow channels, respectively. L_1, L_2, Θ_1 and Θ_2 reflect the length and differing angles of the two lateral inflow channels, respectively. The top width of the two lateral inflow channels and the primary channel are T_1, T_2 and T_3. At a time interval dt, the net amount of fluid that reaches the cell dx is taken into consideration.

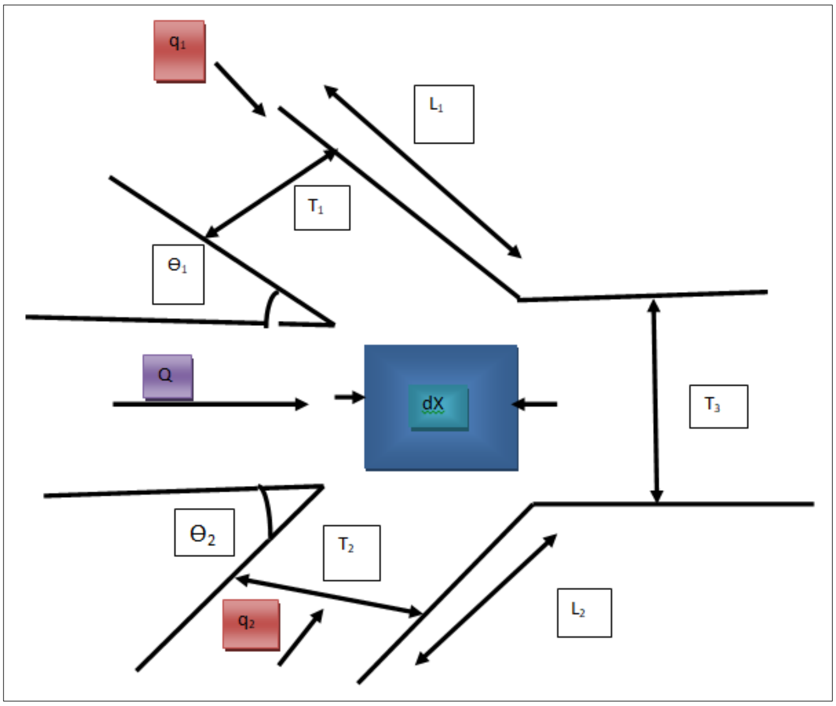

Fig 1: Mathematical model case

Assumption to be adopted:

1. The fluid is Newtonian
2. The fluid is considered incompressible where density is constant everywhere. $\rho = constant$
3. unsteady flow (Changes in fluid variables relative to time at a point)
4. Gravity alone is responsible for the forces causing the flow, and other forces produced in the junction region are ignored.
5. The flow is one-dimensional, with the majority of momentum happening around the x-axis and being completely dependent on x.
6. The length, diameter, depth and angles of the two inflow channels should be directly proportional to each other
   $L_1 = L_2$, $T_1 = T_2$, $y_1 = y_2$ $\Theta_1 = \Theta_2$
7. There is no substantial accumulation of small particles between the primary open channel and the two lateral inflow channels.
8. There is no major turbulent development between the primary open channel and the two lateral inflow channels.

We consider approximation solutions by using the finite difference method and, more importantly, the use of MATLAB tools to derive the results in diagrams, using the conditions above and combining with the continuity equation and momentum equation of motions, which will yield nonlinear solutions.

Mathematical formulation

Continuity equation (Conservation of mass)

The continuity equation is a type of differential equation that describes the movement of a conserved quantity, such as mass. Continuity equation governing flow in an open channel that isn't consistent of any shape is provided by,

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (3)$$

From the model above the cell with lateral inflow dx, in a dt-interval, is considered total volume is $\frac{dQ}{dx} dxdt$.
Discharge on the two lateral inflow channels will be twice $\frac{q}{L}\sin\theta\, dxdt$ because it has been inclined at an angle Θ while increment of fluid is $\frac{dA}{dt} dxdt$ and density is constant. Using conservation law of fluid, we have

$$\frac{dQ}{dx} dxdt + \frac{dA}{dt} dxdt = \frac{q_1}{L_1}\sin\theta_1\, dxdt + \frac{q_2}{L_2}\sin\theta_2\, dxdt \qquad (4)$$

According to Macharia *et al.* (2014) [19] and since the assumption shown above that

$$q_1 + q_2 = 2q\; q_1 = q_2\; L_1 = L_2 = L\; \theta_1 = \theta_2 = \theta$$

Hence

$$\frac{dQ}{dx} dxdt + \frac{dA}{dt} dxdt = 2\frac{q}{L}\sin\theta\, dxdt \qquad (5)$$

It can be reduce to

$$\frac{dQ}{dx} + \frac{dA}{dt} = 2\frac{q}{L}\sin\theta \; (6)$$

A conserved quantity can neither decrease nor increase; it can only shift from one location to another. The equation, by Tsombe *et al.* (2011) [13], is

$$T\frac{\partial y}{\partial t} + VT\frac{\partial y}{\partial x} + A\frac{\partial V}{\partial x} - q = 0 \qquad (7)$$

Substituting equation (6) to equation (7) and arranging we get

$$\frac{\partial y}{\partial t} + V\frac{\partial y}{\partial x} + \frac{A}{T}\frac{\partial V}{\partial x} = 2\frac{q}{TL}\sin\theta \qquad (8)$$

Equation (8) is the general equation of continuity for open channel flow with two lateral inflow channels at an angle.

Momentum equation

The momentum equation is used to describe the motion of fluid particles. This equation is derived from Newton's second law of motion, along with the statement that fluid stress is the sum of the viscous diffusing term plus a pressure term. This is the pace at which the system's linear momentum changes over time. From the model above in a dt-interval, the total momentum for the cell dx is $\frac{\partial QV}{\partial x} dxdt$. The lateral inflow component of velocity in the flow direction is $u\cos\theta$. Thus, lateral inflow momentum into cell dx at a time interval dt becomes $\frac{q}{L}\sin\theta\, u\cos\theta dxdt$.

The fluid pressure and fluid weight in the direction of flow are $g\frac{\partial (yA)}{\partial x}dxdt$ and $gA\,(S_f - S_O)dxdt$ respectively. The momentum increment for the dx cell is $\frac{\partial Q}{\partial t}\,dxdt$. Accordingly, In the momentum equation we have, according to the conservation law, where

$$\frac{\partial Q}{\partial t}dxdt + \frac{\partial QV}{\partial x}dxdt + g\frac{\partial (yA)}{\partial x}dxdt + gA(S_f - S_o)dxdt = 2\frac{q}{L}\sin\theta\, u\cos\theta\, dxdt \quad (9)$$

Noting that Q = AV

Substituting and rearranging the equation, we get

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} + g(S_f - S_o) = 2\frac{q}{AL}\sin\theta\,(u\cos\theta - V) \quad (10)$$

Equation (3.8) is the general momentum equation of an open channel with two lateral inflow channels at varying angles.

Solution procedure

Since the governing equations (8) and (10) are nonlinear and thus cannot be solved numerically. Specifically, using the finite difference approach to diffuse scheme.

We take

$$\frac{\partial v}{\partial t} = \frac{v(i,j+1) - v(i,j))}{\Delta t} \quad (11)$$

$$\frac{\partial y}{\partial t} = \frac{y(i,j+1) - y(i,j))}{\Delta t} \quad (12)$$

$$\frac{\partial v}{\partial x} = \frac{v(i+1,j) - v\,(i-1,j)}{2\Delta x} \quad (13)$$

$$\frac{\partial y}{\partial x} = \frac{y(i+1,j) - y\,(i-1,j)}{2\Delta x} \quad (14)$$

Substituting the equation (11), (12), (13) and (14) to equation (8)

$$\frac{y(i,j+1) - y(i,j)}{\nabla t} + v(i,j)\left(\frac{y(i+1,j) - y\,(i-1,j)}{2\Delta x}\right) + \frac{A}{T}\left(\frac{v(i+1,j) - v\,(i-1,j)}{2\Delta x}\right) = \frac{2q}{TL}\sin\theta \quad (15)$$

Rearranging we get

$$y(i,j+1) = \Delta t\left(-v\,(i,j)\left(\frac{y(i+1,j) - y\,(i-1,j)}{2\Delta x}\right) - \frac{A}{T}\left(\frac{v(i+1,j) - v\,(i-1,j)}{2\Delta x}\right) + \frac{2q}{TL}\sin\theta\right) + y\,(i,j) \quad (16)$$

Also substitute equation (10), We get

$$\frac{v(i,j+1) - v\,(i,j)}{\Delta t} + v(i,j)\left(\frac{v(i+1,j) - v(i-1,j)}{2\Delta x}\right) + g\left(\frac{y(i+1,j) - y\,(i-1,j)}{2\Delta x}\right) + g(S_f - S_O) = \frac{2q}{TL}\sin\theta(u\cos\theta - v\,(i,j)) \quad (17)$$

Rearranging we get

$$v(i,j+1) = \Delta t\left(-v(i,j)\left(\frac{v(i+1,j) - v(i-1,j)}{2\Delta x}\right) - g\left(\frac{y(i+1,j) - y\,(i-1,j)}{2\Delta x}\right) - g(S_f - S_O) + \frac{2q}{TL}\sin\theta(u\cos\theta - v\,(i,j))\right) + v\,(i,j) \quad (18)$$

The velocity u_o = 10 m/s and channel depth y_o = 0.5 m are now used as the original and boundary conditions in the form of finite differences.

Initial conditions,

$y(0,x) = 0\; v(0,x) = 0$ (19)

The boundary conditions

$y(t,x_{initial}) = 30\; v(t,x_{initial}) = 20$ (20)

$y(t,x_{final}) = 10\; v(t,x_{final}) = 20$ (21)

Very small values of Δt are used to solve the two equations. We have set Δx = 0 and Δt = 0.0 in this analysis. It is understood that this finite difference process is convergent and numerically stable. The number of sub-divisions was taken to be 5 along the channel while it was taken to be 20 sub-divisions over the period. With reference to Kazezyilmaz-Alhan (2012) [5] appropriate slope for simulation range between 0.001 and 0.0001 hence we choose 0.002.

The following constants were also considered:

$$T = 1 \; L = 1 \; q = 0.3 \; \theta = \frac{\pi}{3} = 60^0 \; g = 9.82 \; n = 0.01 \; R = 1.1$$

Results and Discussion

The MATLAB software is used to simulate the equations (16) and (18) which appear in Appendix. This was done by varying i and j at various nodal points. Then the three graphs were plotted using the values of the velocity and the time at a certain location. Various flow parameters of area, length and angle were investigated to determine how they affect the velocity.

Results

Table 1: Velocity versus time: Angle = pi/4, pi/3, pi/2.5, pi/2

Time (s)	Velocity (m/s/s)			
	pi/4	pi/3	pi/2.5	pi/2
0	0	0	0	0
0.05	0.016	0.014	0.0098	0.001
0.1	0.032	0.0279	0.0196	0.002
0.15	0.0479	0.0419	0.0294	0.003
0.2	0.0639	0.0558	0.0392	0.004
0.25	0.0798	0.0697	0.0489	0.005
0.3	0.0957	0.0835	0.0586	0.006
0.35	0.1115	0.0973	0.0682	0.0069
0.4	0.1272	0.111	0.0778	0.0077
0.45	0.1429	0.1247	0.0872	0.0084
0.5	0.1585	0.1382	0.0966	0.009
0.55	0.1741	0.1517	0.1059	0.0096
0.6	0.1895	0.165	0.115	0.01
0.65	0.2048	0.1782	0.1241	0.0102
0.7	0.22	0.1913	0.133	0.0103
0.75	0.2351	0.2043	0.1417	0.0103
0.8	0.2501	0.2172	0.1503	0.01
0.85	0.265	0.2299	0.1588	0.0096
0.9	0.2797	0.2425	0.1671	0.009
0.95	0.2943	0.2549	0.1752	0.0082
1	0.3088	0.2672	0.1832	0.0072

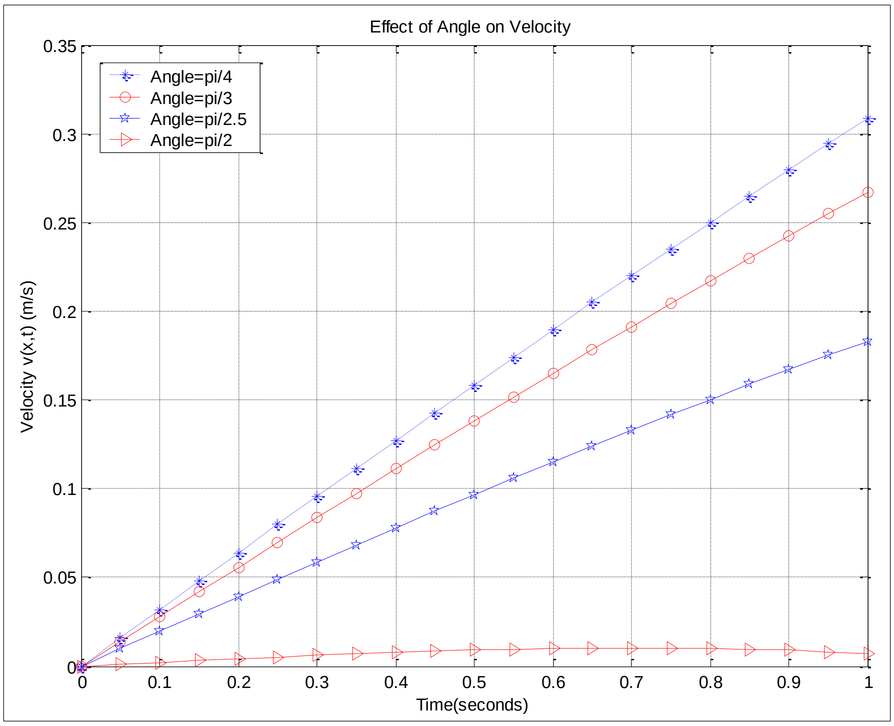

Fig 2: Effect of angle on velocity

Discussion

Figure 2 shows that the rise in the angle above 45^0 contributes to a decrease in the velocity of the flow. The flow velocity is constant at 90^0, indicating no impact induced by the fluid from the lateral inflow channels, and from the above assumption, we conclude that the flow is laminar, so there is no turbulence in the junction.

The inflow channel angle of 45^0 is the most efficient angle for further discharge.
In general, we advise designers to consider the angle of 45^0 for optimum discharge to occur in flat areas.

Conclusion

The goal was to look at the impact of the angle of the lateral inflow channels on the main channel flow velocity. The summary of the angle effect shows that 90^0 does not affect the key channel's flow velocity. 72^0 and 60^0 increases but 45^0 increases more the flow velocity.

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