Flow Over Consecutive Heated Cylinders For Dynamic Fruit Cooling System

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Abstract

This case study aims to study the outlet temperature profiles of different fluids after they gain heat from fruits which emit constant heat flux. The 2D case setup is a channel with three cylindrical cavities in line, giving out constant heat flux equal to the heat of respiration of the fruits. The temperature rise of the fluid can be used to estimate the power required to cool down the fluid back to inlet temperature and estimate and optimise the costs of making compact alternatives for cold storages. It analyses steady state flow profiles in the laminar region and also the extent of differences in temperature and velocity contours with changing fluid, heat flux and inlet velocities.

1. Introduction

Storing fruits in an economical and compact manner is a problem many producers especially in rural areas face. Generally, a cold storage design involves a large room with insulations and eutectic mixtures as layers to prevent heat ingress. However, the cartons which are in the most intimate proximity of the fruits are not so well designed to optimise this process. So in my project I came up with an idea of having a dynamic fluid cooling system in which a fluid (water, ethylene glycol or glycerine) flows over three fruits (considered as constant heat flux emitting cylinders) kept in line and hence gains some amount of heat. The power required to take the fluid back to the inlet temperature and recycle it etc can be factors which could be considered for comparing its utility compared to conventional cold storages.

Various factors influence the flow regime and temperature profiles such as flux ingress, inlet velocity and properties of the fluid which have been discussed further.

2. Problem Statement

The problem, for solving in OPEN FOAM has been simplified by assuming fruits as cylinders and considering uniform heat flux F being emitted from the cylinder surface. The fluid A enters the channel at 280K at a uniform velocity V ensuring laminar regime. It flows over the heated cylinders and proceeds towards the subsequent ones. Analysis of the flow profile due to repetitive obstacles and the final outlet temperature are to be analysed along with their variation with V, F and A.

3. Governing Equations

The governing equations involved are straightforward mass and momentum balance equations. Constant density has been assumed since the variation in temperature is very small (of the order 10^ (-3))

2D equations

Mass balance: $\rho\nabla\cdot(V) = 0$

Momentum balance: $\rho\frac{D(V)}{Dt} = -\nabla P + \mu\nabla^2 V + \rho g$ (steady state, ρ constant, μ constant, g effect neglected)

$$\rho\left(V_x\frac{\partial V_x}{\partial x} + V_y\frac{\partial V_x}{\partial y}\right) = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 V_x}{\partial x^2} + \frac{\partial^2 V_x}{\partial y^2}\right)$$

$$\rho\left(V_x\frac{\partial V_y}{\partial x} + V_y\frac{\partial V_y}{\partial y}\right) = -\frac{\partial P}{\partial y} + \mu\left(\frac{\partial^2 V_y}{\partial x^2} + \frac{\partial^2 V_y}{\partial y^2}\right)$$

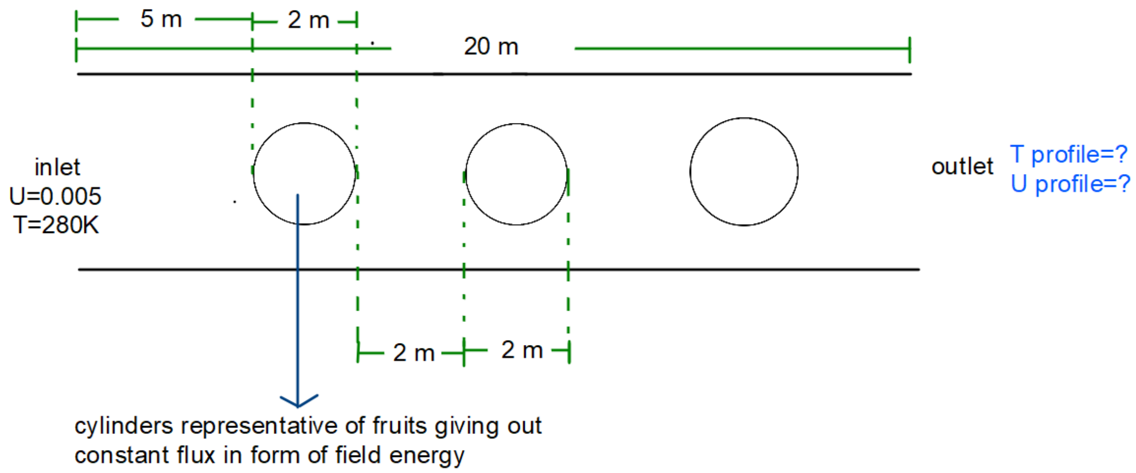
Energy Balance: $\rho C_p\frac{DT}{Dt} = \mathrm{k}\nabla^2 T + \mu\varphi_v$

$$\rho C_p\left(V_x\frac{\partial T}{\partial x} + V_y\frac{\partial T}{\partial y}\right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \mu[2(\frac{\partial V_x}{\partial x}^2) + 2\left(\frac{\partial V_x}{\partial x}^2\right) + (\frac{\partial V_y}{\partial x} + \frac{\partial V_x}{\partial y})^2]$$

4. Simulation Procedure

4.1 Geometry and Mesh

The required geometry with details is as follows:



The mesh has been made using the blockMeshDict utility of OPEN FOAM. The system had been divided into 52 blocks. These can be divided as follows:

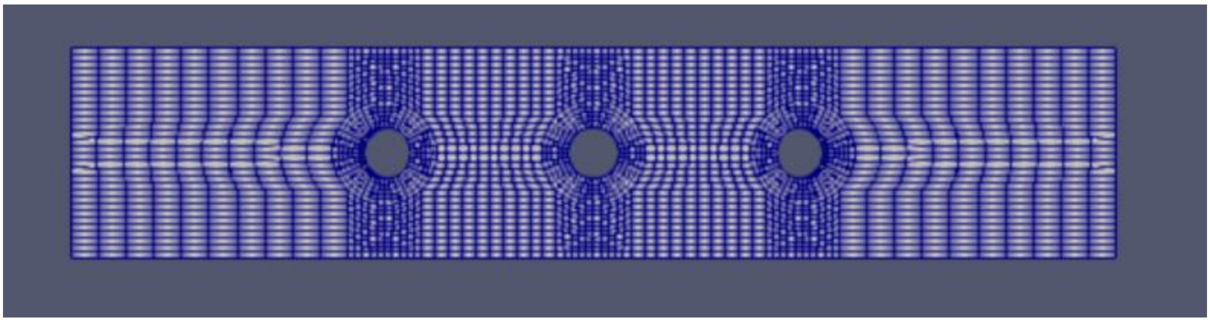
a) 8 rectangular blocks with divisions (80,80,1)

b) 8 semi rectangular horizontal blocks (80,40,1)

c) 12 semi rectangular vertical blocks (40,80,1)

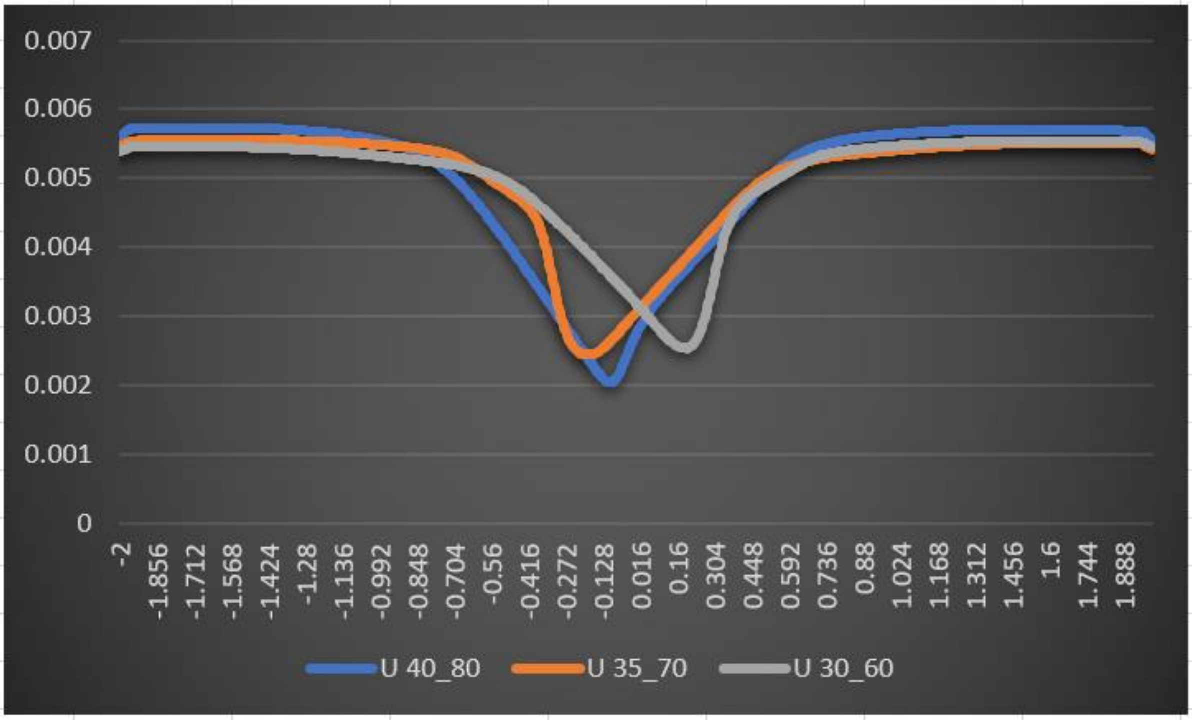
d) 24 arched blocks (40,40,1)

The grading used was (1 1 1)



The actual mesh is much finer than the one shown which is a schematic.

The grid independence study was performed with corresponding mesh sizes as (30,60) (35,70) and (40,80) The results tabulated can be seen as follows:



The average error between velocities of the corresponding grid sizes are as follows:

40_35 : 0.000225

35_30 : 0.000233

30_40 : 0.000381

It can be concluded that since the error between the finest and intermediate mesh is the least followed by the intermediate and coarse, the mesh has become better by refinement and since the order of error is small, it can be assumed to be independent. (further refinement has not been done due to lack of competency of the personal system)

4.2 Initial and Boundary Conditions

The initial conditions for the inlet stream and heated cylinders are :

Water

Case I : U=0.005, T=280K, F=0.0339 W/m^2

Case II : U=0.005, T=280K, F=0.0612 W/m^2

Case III : U=0.005, T=280K, F=0.1428 W/m^2

Case IV : U=0.1, T=280K, F=0.0339 W/m^2

Case V : U=1, T=280K, F=0.0339 W/m^2

Ethylene Glycol

Case VI : U=0.005, T=280K, F=0.0339 W/m^2

Glycerine

Case VII : U=0.005, T=280K, F=0.0339 W/m^2

The common boundary conditions for all the cases are:

1. **Temperature T:**
   Internal Field : uniform 280
   Inlet : Fixed Value (280)
   Outlet, Adiabatic top and bottom walls : Zero Gradient
   Heated Cylinders : Fixed Gradient (Value: F*alpha_fluid)

2. **Velocity U:**

   Internal Field: (0 0 0)

   Inlet : Fixed Value (U)

   Outlet : Zero Gradient

   Heated Cylinders, Adiabatic top and bottom walls : No Slip

3. **Pressure p_rgh**

   Internal Field : uniform 1e5

   Inlet, Adiabatic top and bottom walls, heated cylinders : fixedFluxPressure (0)

   Outlet : prgh pressure (Value: 10e5; P: 10e5)

4. **Pressure p**

   Internal Field : uniform 1e5

   Inlet, Outlet, Adiabatic top and bottom walls, heated cylinders : Calculated

5. **Thermophysical Properties**

   type heRhoThermo;

mixture pureMixture;

transport const;

thermo hConst;

equationOfState rhoConst;

specie specie;

energy sensibleInternalEnergy;

Other Properties specified in the Thermophysical and Transport properties are as follows:

Fluid	**Mol. Wt**	**Density(kg/m3)**	**Cp(J/kgK)**	**k**	**Mu(m2/s)**	**Pr**
Water	18.02	1000	4198	582e-3	1.422e-6	10.26
Ethylene Glycol	62.0678	1125.8	2323	244e-3	37.3e-6	617
Glycerine	92.09	1271.9	2298	284e-3	4200e-6	43200

4.3 Solver

The solver used in this simulation is buoyantSimpleFoam which is a steady state solver for buoyant, turbulent flows of compressible fluids including radiation for ventilation and heat transfer solving heat transfer in flow problems. It works on the SIMPLE algorithm.The equations it uses are:

1. **Mass conservation** (continuity): $\nabla \cdot (\rho \boldsymbol{u}) = 0$ $[\rho : Fluid\ Density\ \&\ V\!: Fluid\ Velocity]$

2. **Momentum Conservation** : $\nabla.(\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla.\left(2\mu_{eff} D(\boldsymbol{u})\right) - \nabla(\frac{2}{3}\mu_{eff}(\nabla.\boldsymbol{u})) + \rho \boldsymbol{g}$

[p: static pressure field; **g:** gravitational acceleration; μ_{eff}: sum of molecular and turbulent viscosity; D($\boldsymbol{u}$): rate of strain tensor i.e. $\frac{1}{2}(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^{\boldsymbol{T}})$]

For implementation in Open Foam, the ∇p and g terms are arranged to form p_rgh = p-$\rho g \boldsymbol{r}$

Where **r** is the position vector.

3. **Energy Conservation :**Sensible Internal Energy model

$$\nabla.(\rho \boldsymbol{u} e) + \frac{\partial(\rho K)}{\partial t} + \nabla.(\rho \boldsymbol{u} K) + \nabla.(p\boldsymbol{u}) = \nabla.\left(\alpha_{eff}\nabla e\right) + \rho \boldsymbol{u}.\boldsymbol{g}$$

Where K= $|u^2|/2$ i.e. Kinetic Energy per unit mass

α_{eff} is given by $\frac{\rho \nu_t}{Pr_t} + \frac{\mu}{Pr}$ where symbols have their usual meanings.

5. Results and Discussions

The general result observed is that as the flow crosses over consecutive cylinders, the temperature rises and the velocity starts having a considerable y component. The vortices in flow become prominent as steady state approaches. The general contour can be viewed as follows:

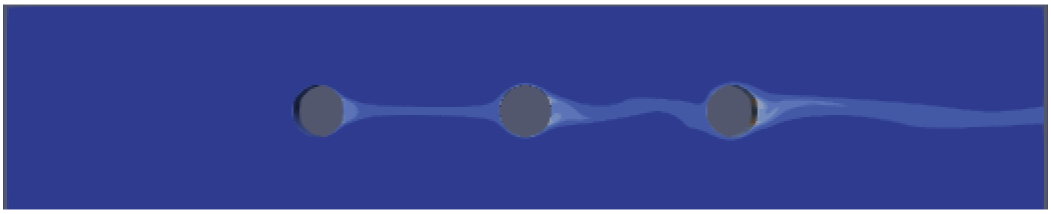


Fig: Temperature contours throughout the channel

The effect of Heat Flux value, Inlet Velocity value and fluid chosen have been analysed and conclusions have been drawn.

5.1 Heat Flux Values

The constant heat flux entering via the three cylinders has been varied keeping other properties constant (U=0.005, Fluid: water). The outlet velocity and temperature profiles have been observed.

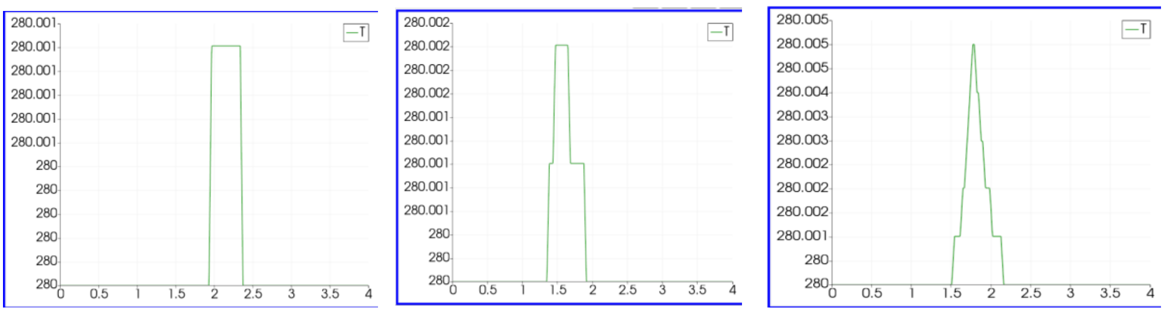


Fig : Outlet temperature profiles for flux values 0.0339, 0.0612, 0.1428 W/m^2 respectively

As heat flux increases, the maximum temperature reaches higher maximum values. The profile shows that with increasing flux the distribution of heat becomes more pronounced in the region spanned by the cylinders and has a higher prominence. The average temperature which can be approximated by $\frac{\int_0^4 T dy}{\int_0^4 dy}$ can be approximated by area under the curve divided by 4. The *highest average temperature is found to be for the highest heat flux* case as was expected.

The effect of heat flux on velocity can be studied by plotting the velocity against the y coordinates as follows:

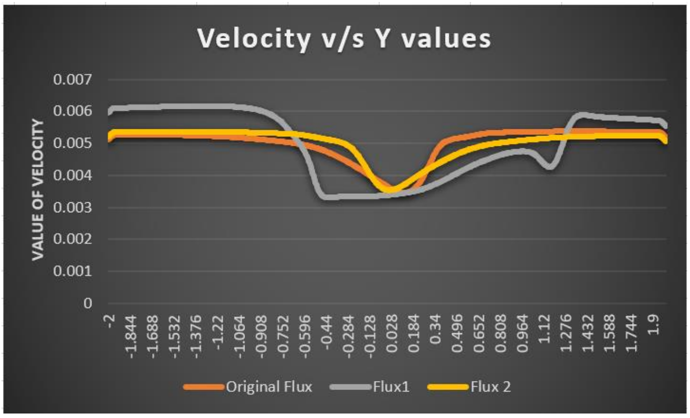


Fig: Exit velocity profiles for different heat flux values

The average velocities for the three cases come out to be 0.005, 0.0051 and 0.005 respectively and so it can be concluded that since we had assumed constant density condition, the value of heat flux influenced only the outlet temperature and not the velocity.

The velocity and temperature contours at steady state match indicating that there might be some relation between both the parameters. Hence the next parameter would be inlet velocity.

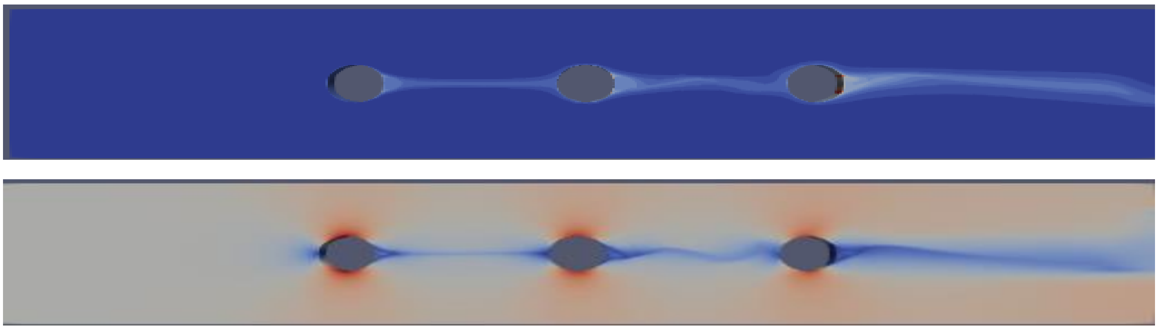
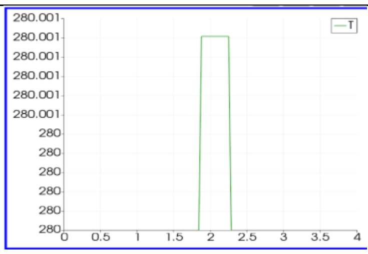
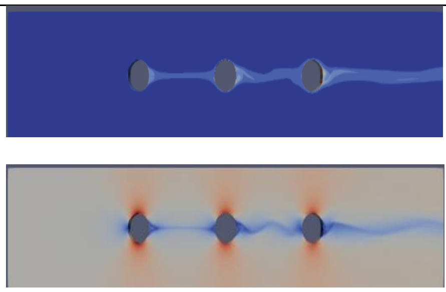
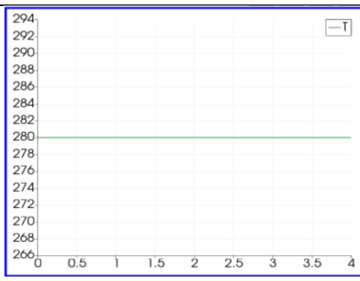
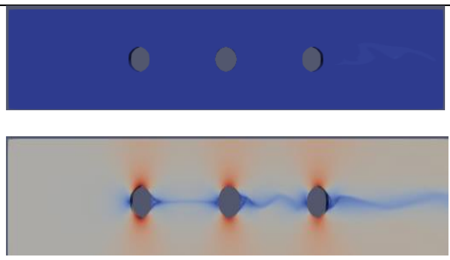
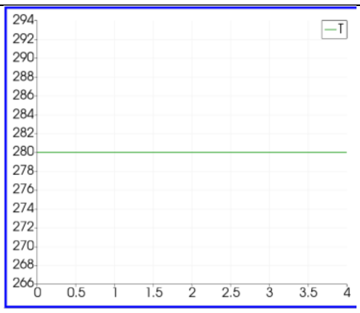
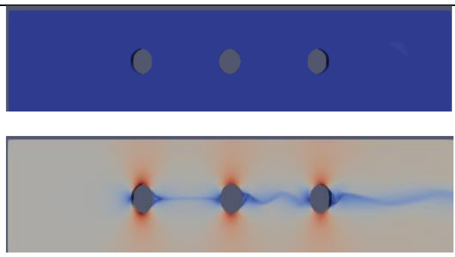


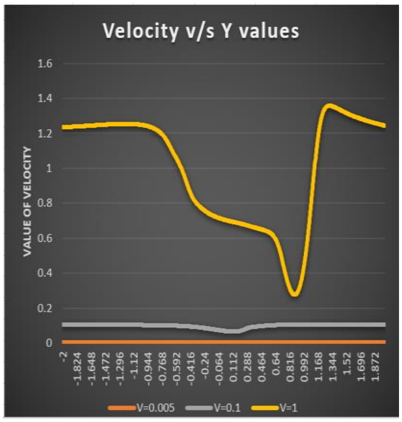
Figure: Temperature and velocity contour for Flux value 0.0612 W/m^2

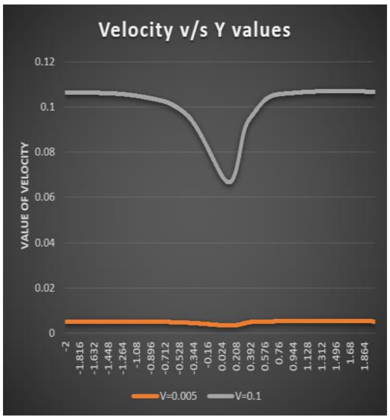
5.2 Inlet Velocity

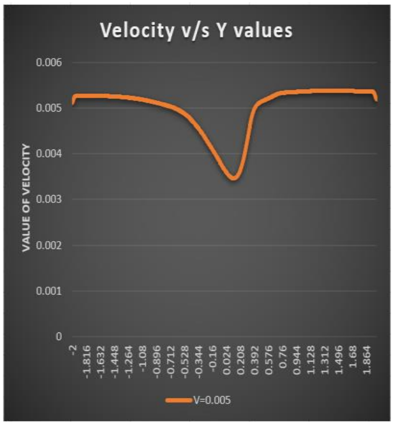
The constant velocity with which the fluid is entering has been varied keeping other properties constant (F=0.0339, Fluid: water). The outlet velocity and temperature profiles have been observed.

	Temperature Profile	Temperature/Velocity Contour
U=0.005		 t=1000 sec
U=0.1		 t=480 sec
U=1m/s		 t=460 sec

As velocity increases, steady state with very negligible non detectable variation in outlet temperature profile is achieved in a lower time span. The outlet velocity profiles for all the 3 cases can be seen as follows:



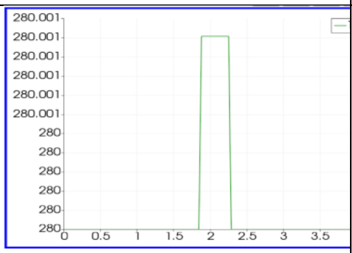
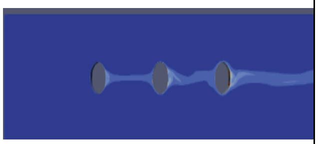
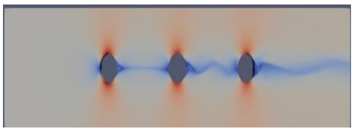
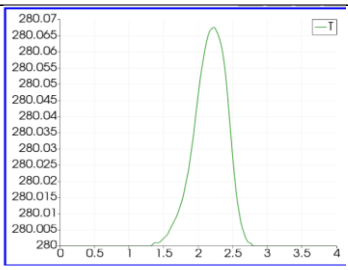
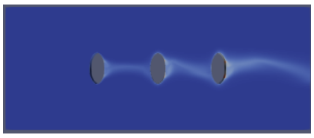
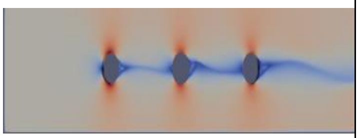
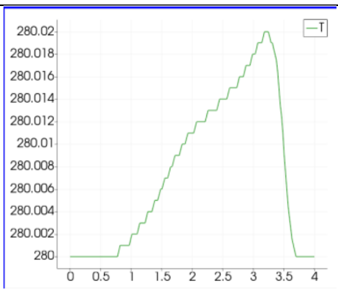
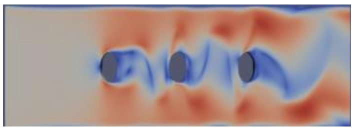




It can hence be concluded that as velocity would increase the system would attain steady state faster and would give a somewhat constant outlet temperature profile which would be beneficial for our operation. The trend of velocity profile is similar in all three cases.

5.3 Changing Fluid Properties

The fluid properties have been varied (chosen for Water, Ethylene Glycol and Glycerine as mentioned in section 4.2) keeping other parameters constant (F=0.0339, U=0.005). The outlet velocity and temperature profiles have been observed for each of the fluid and come out to be as follows:

<table>
<tr><th></th><th>Temperature profile</th><th>Temperature Contour</th><th>Velocity Contour</th></tr>
<tr><td>Water</td><td>
</td><td></td><td></td></tr>
<tr><td>Ethylene Glycol</td><td>
</td><td></td><td></td></tr>
<tr><td>Glycerine</td><td>
</td><td></td><td></td></tr>
</table>

The comparison of velocity profiles can be seen as follows:

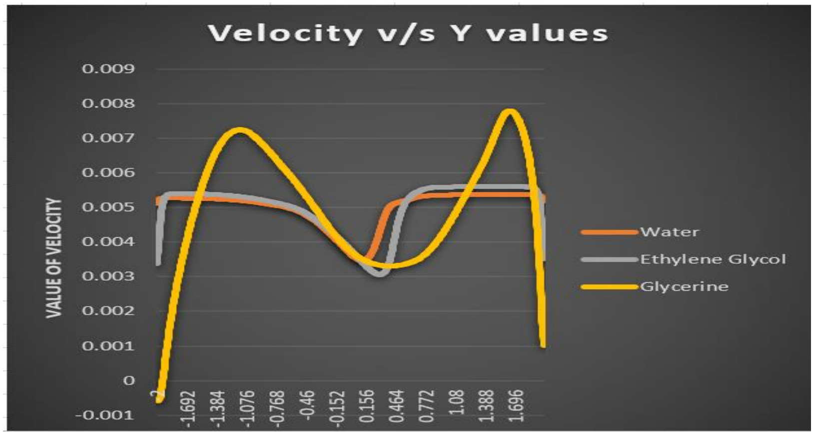


Figure: Outlet velocities plotted against values of y for different fluids

It can be concluded that since Glycerine has highest viscosity ,its velocity profile is slightly different than the other two. The vortices formed are large and smooth and follow the no slip condition pretty well. Separation of flow can also be observed better in Glycerine because of a more laminar characteristic. The temperature profiles reflect that the temperature rise in ethylene Glycol is maximum and so it can also be concluded that temperature rise does not only depend on the Cp values (which is least for Glycerine) but other factors like nature of flow, Viscosity and density also play a major role especially when obstacles like the ones in this case become prominent.

5.4 Conclusion

Outlet temperature increases with increase in the flux ingress and this is a uniform result. As the inlet velocity is increased, the intensity of vortex formation and flow separation reduces, rendering very few fluctuations in temperature of outlet which becomes almost uniform at steady state. The fluid properties play a major role in determining hor the temperature rise would look like. For velocity, in almost all the cases considered, Flux did not play a major role in determining velocity however the nature of fluid caused the velocity profile, its streamlines and vortices to vary.

Using a fluid such as Water at higher velocities and nominal heat ingress can be used to implement in a dynamic system such as this.

References

I. Chiu , W. K. S., Richards , C. J., and Jaluria, Y. (February 1, 2001). "Experimental and Numerical Study of Conjugate Heat Transfer in a Horizontal Channel Heated From Below ." ASME. J. Heat Transfer. August 2001; 123(4): 688–697. https://doi.org/10.1115/1.1372316

II. Ostrach, S., and Kamotani, Y. (May 1, 1975). "Heat Transfer Augmentation in Laminar Fully Developed Channel Flow by Means of Heating From Below." ASME. J. Heat Transfer. May 1975; 97(2): 220–225. https://doi.org/10.1115/1.3450344