Report

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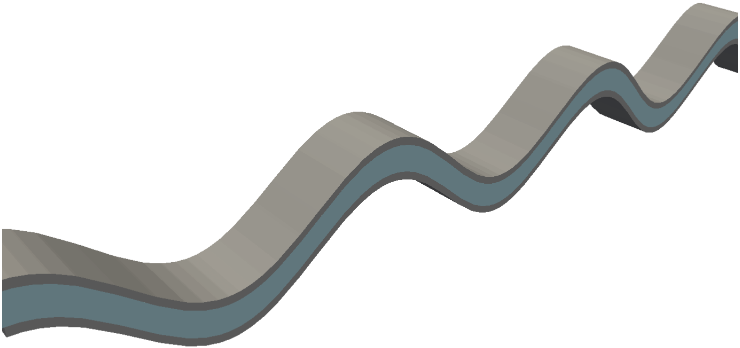
March 28, 2014

Introduction

Conjugate heat transfer simulations have been conducted on a range of designs for single tubes for use in heat exchangers. This report provides preliminary data on several designs as well as a further understanding in modelling approaches for use in further work.

Overview of simulations

Using CAD models provided by Hieta conjugate heat transfer simulations have been performed on single tube designs. In each simulation 0.046m of the single tube is subject to a constant temperature on the solid boundary. The steady state temperature, velocity, pressure and density fields are then found using the chtMultiRegionSimpleFoam openFOAM solver.



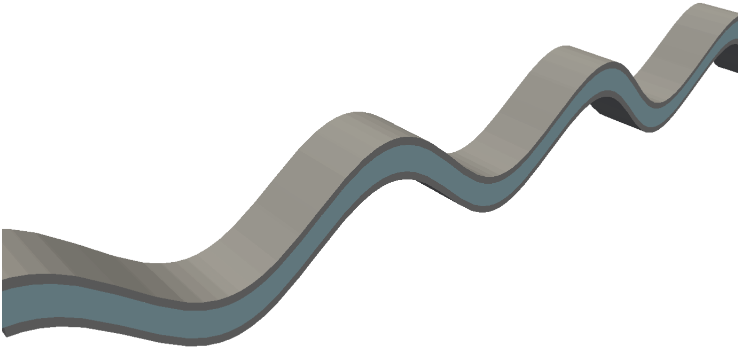
Example of single tube geometry (wavy 17). Blue, grey represent the fluid, solid regions respectively.

Overview of simulations

In this project 5 different single tube designs are subjected to a constant mass flow rate of 2.94e-6 Kg/s. In a cylindrical tube of 1mm diameter this corresponds to a Reynolds number of 200.

Further simulations have been carried out at higher Reynolds numbers where possible to investigate the trend between higher Reynolds numbers and pressure drop/heat transfer.

In addition further simulations have been carried out to try and investigate the prediction of transition of the flow to one dominated by unsteady behaviour for the wavy tube class of models.



Example of single tube geometry (wavy 17). Blue, grey represent the fluid, solid regions respectively.

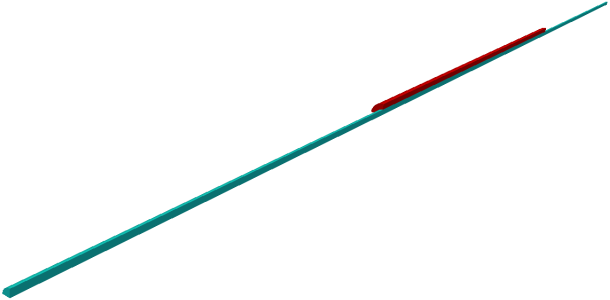
Material properties and boundary conditions

Region properties and flow conditions are given below. Temperature dependent functions of thermal conductivity/specific heat capacity can also be used if required in OpenFOAM versions 2.2.0 and above. No surface wall roughness is modelled. The inlet and outlet sections of the CAD model have been extended to reduce sensitivity of the domain of interest to the boundary conditions.

	Fluid region	Solid region
Mass flow inlet (Kg/s)	2.93e-6	
Pressure outlet (N/m^2)	101325	
Fixed inlet temperature (K)	293	
Fixed boundary temperature (K)		375

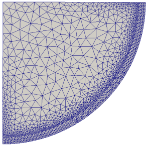
	Fluid region	Solid region
Density (Kg/m^3)	Ideal gas law	8193.25
Viscosity (Ns)/m^2)	Sutherland law	
Thermal conductivity (W/mK)	Calculated	14
Specific heat capacity (J/KgK)	1006.43	435

Table 1: Boundary conditions and material properties

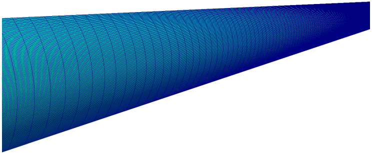


Screenshot of cylinder geometry

Hydraulic diameter	0.001m
Entrance length	0.036m
Heated length	0.046m
Exit length	0.036m



Cross sectional slice of mesh

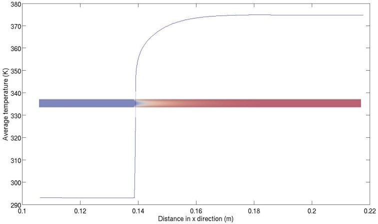


Lengthwise visualisation of mesh

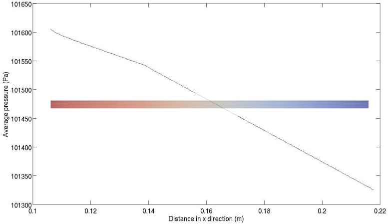
The cylindrical mesh consists of 3430260 prism elements for the fluid region and 2330360 hexahedral elements for the solid region.

As a check on the mesh dimension an isothermal simulation was run to calculate the friction factor which is well known. The mesh generated a friction factor with an error of less than 3%.
The cylindrical model has two planes of symmetry and so we can reduce the mesh size to a quarter to lessen computational cost considerably. The model is solved using the boundary conditions and property calculations as Table 1. For different Reynolds numbers we change simply the mass flow rate (which translates to a inlet velocity change) and these are given explicitly in the spreadsheet provided.

Results - cylinder velocity/temperature visualisation



Plot of average temperature along x axis



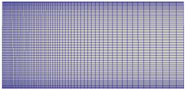
Plot of average pressure along x axis

For a typical cylindrical case the data is found by taking incremental slices of the model in the z -axial direction and taking the average of each variable over each slice. We see that pressure drop is linear as expected with the gradient increasing as we enter the heated section of the pipe. At low Reynolds number the fluid gets heated quickly.

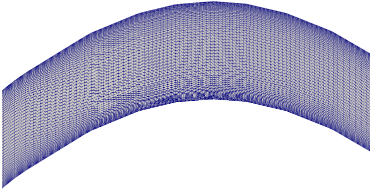
Results - wavy17 model

In the wavy17 model a rectangular duct of height 1mm and width 4.17mm is projected along a sine wave of amplitude 1.644mm and wavelength 12.35mm.

Hydraulic diameter	0.00161m
Entrance length	0.037m
Heated length	0.046m
Exit length	0.037m



Cross sectional slice of mesh



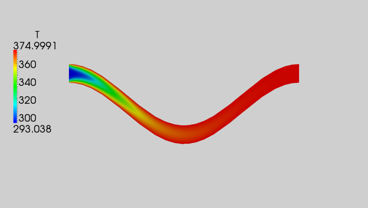
Lengthwise visualisation of mesh

The wavy17 mesh consists of 6160050 hexahedral elements for the fluid region and 2894136 hexahedral elements for the solid region.

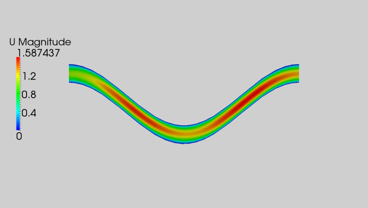
As a check on the mesh dimension an isothermal simulation was run to calculate the friction factor which is well known. The mesh generated a friction factor exactly to 3 significant figures.
The wavy17 model has a plane of symmetry and so we can reduce the mesh size to a half to lessen computational cost considerably. The model is solved using the boundary conditions and property calculations as Table 1. For different Reynolds numbers we change simply the mass flow rate (which translates to a inlet velocity change) and these are given explicitly in the spreadsheet provided.

Results - wavy 17 velocity/temperature visualisation

In the wavy17 model a rectangular duct of height 1mm and width 4.17mm is projected along a sine wave of amplitude 1.644mm and wavelength 12.35mm.



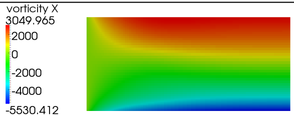
First wavelength coloured by temperature contour



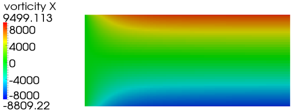
First wavelength coloured by $|U|$ contour

The plots show the first wavelength of the heated section coloured by velocity magnitude and temperature. At this massflow rate the flow is still attached because the Reynolds number is much lower. This means we avoid the regions of low velocity fluid resulting in the high velocity stream as in the wavy3 model. We see that despite the symmetry of the geometry in the lengthwise direction the velocity at the outlet is higher than the inlet. This is because as the fluid is getting heated the density is decreasing. The volumetric flow rate must increase to preserve massflow rate.

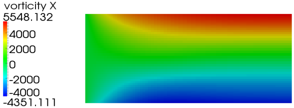
Results - wavy 17 vorticity visualisation



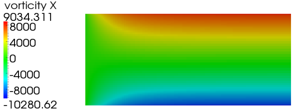
z = 0L



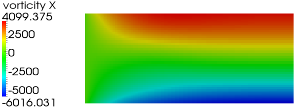
z = 0.25L



z = 0.5L

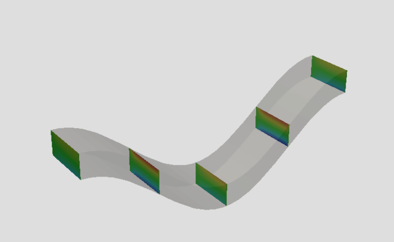


z = 0.75L

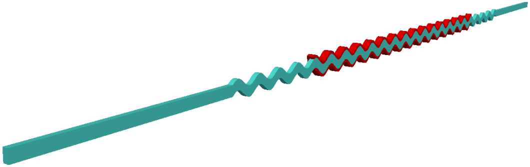


z = 1L

The images show slices of the cross sectional area coloured by the x component of vorticity taken at increments of 0.25 wavelength. The data suggests that in-between peaks and troughs have stronger alternating areas of local rotation. The vorticity is fairly evenly distributed between the upper and lower walls.

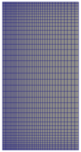


In the wavy3 model a rectangular duct of height 1mm and width 1.03mm is projected along a sine wave of amplitude 0.408mm and wavelength 3.07mm.

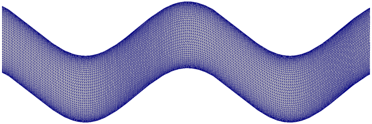


Screenshot of cylinder geometry

Hydraulic diameter	0.00103m
Entrance length	0.033m
Heated length	0.046m
Exit length	0.033m



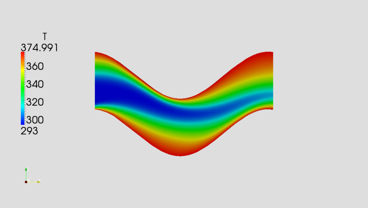
Cross sectional slice of mesh



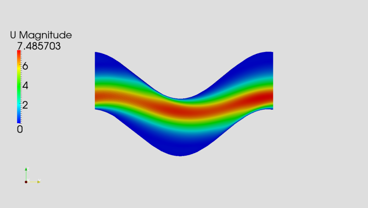
Lengthwise visualisation of mesh

The wavy3 mesh consists of 6277355 hexahedral elements for the fluid region and 4873491 hexahedral elements for the solid region.

As a check on the mesh dimension an isothermal simulation was run to calculate the friction factor which is well known. The mesh generated a friction factor with an error of less than 2%.
The wavy3 model has a plane of symmetry and so we can reduce the mesh size to a half to lessen computational cost considerably. The model is solved using the boundary conditions and property calculations as Table 1. For different Reynolds numbers we change simply the mass flow rate (which translates to a inlet velocity change) and these are given explicitly in the spreadsheet provided.



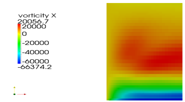
First wavelength coloured by temperature contour (K)



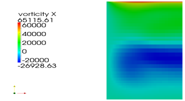
First wavelength coloured by |U| contour (m/s)

The plots show the first wavelength of the heated section coloured by velocity magnitude and temperature. At this mass flow rate this flow has Reynolds number of 163. Even at this low Reynolds number this curvature generates separation at the peaks and troughs which leads to large areas of low velocity flow. Further this means that the flow is made up of a thinner channel of faster moving fluid. This is interesting since, air being a poor conductor of air, having pockets of very still air will reduce the heat transfer in the model. We see that despite the symmetry of the geometry in the lengthwise direction the velocity at the outlet is higher than the inlet. This is because as the fluid is getting heated the density is decreasing. The volumetric flow rate must increase to preserve massflow rate.

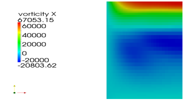
Results - wavy 3 vorticity visualisation



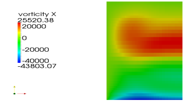
z = 0L



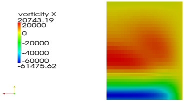
z = 0.25L



z = 0.5L



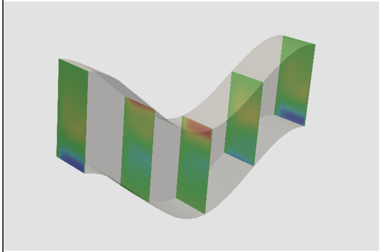
z = 0.75L



z = 1L

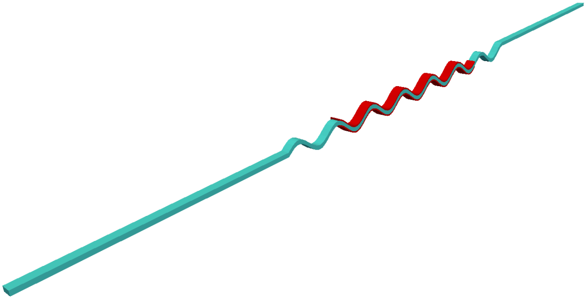
The images show slices of the cross sectional area coloured by the x component of vorticity taken at increments of 0.25 wavelength. The data suggests that in-between peaks and troughs have stronger alternating areas of local rotation.

Compared to the wavy17 model the vorticity is more concentrated at the lower wall at each peak and the upper wall at each trough with very low vorticity in the wells.



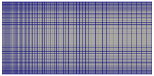
Results - wavy33 model

In the wavy33 model a rectangular duct of height 0.8mm and width 3.33mm is projected along a sine wave of amplitude 1.31mm and wavelength 9.88mm.

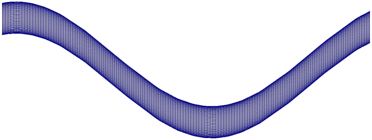


Screenshot of cylinder geometry

Hydraulic diameter	0.00129m
Entrance length	0.0593m
Heated length	0.046m
Exit length	0.0593m



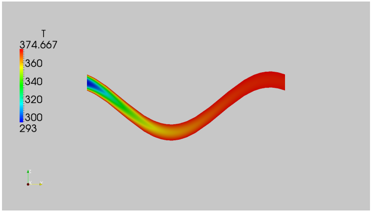
Cross sectional slice of mesh



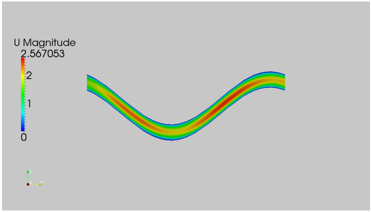
Lengthwise visualisation of mesh

The wavy33 mesh consists of 8848710 hexahedral elements for the fluid region and 2952096 hexahedral elements for the solid region.

As a check on the mesh dimension an isothermal simulation was run to calculate the friction factor which is well known. The mesh generated a friction factor with an error of less than 2%.
The wavy33 model has a plane of symmetry and so we can reduce the mesh size to a half to lessen computational cost considerably. The model is solved using the boundary conditions and property calculations as Table 1. For different Reynolds numbers we change simply the mass flow rate (which translates to a inlet velocity change) and these are given explicitly in the spreadsheet provided.

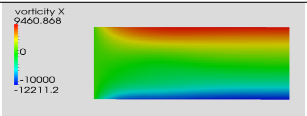


First wavelength coloured by temperature contour

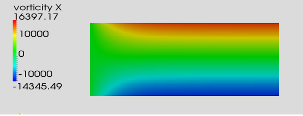


First wavelength coloured by |U| contour

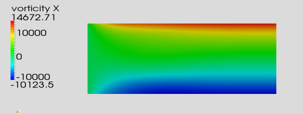
The plots show the first wavelength of the heated section coloured by velocity magnitude and temperature. Again at this mass flow rate we do not get the separation and low velocity regions as in wavy3. We see that despite the symmetry of the geometry in the lengthwise direction the velocity at the outlet is higher than the inlet. This is because as the fluid is getting heated the density is decreasing. The volumetric flow rate must increase to preserve massflow rate.



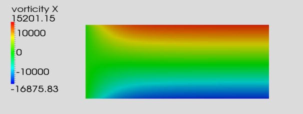
z = 0L



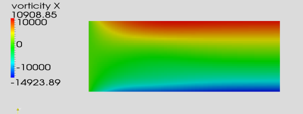
z = 0.25L



z = 0.5L



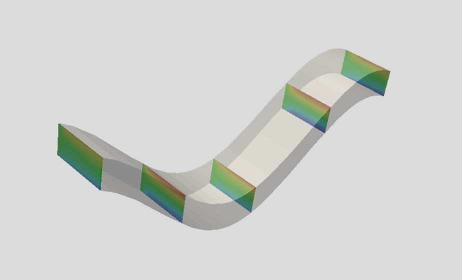
z = 0.75L



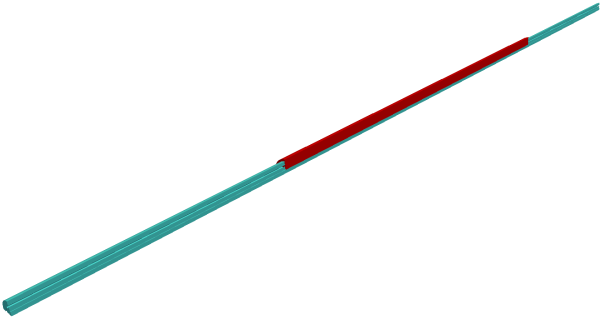
z = 1L

The images show slices of the cross sectional area coloured by the x component of vorticity taken at increments of 0.25 wavelength. The data suggests that in-between peaks and troughs have stronger alternating areas of local rotation.

Compared to the wavy17 model the vorticity is more concentrated at the lower wall at each peak and the upper wall at each trough.



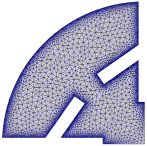
In the 00036 model a cylinder is given fin enhancements. The tube and fin dimensions are designed to still give a hydraulic diameter of 0.001m.



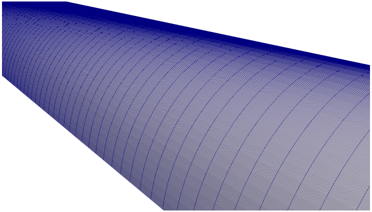
Screenshot of cylinder geometry

Hydraulic diameter	0.001m
Entrance length	0.0384m
Heated length	0.072m
Exit length	0.0384m

Results - 00036 model



Cross sectional slice of mesh

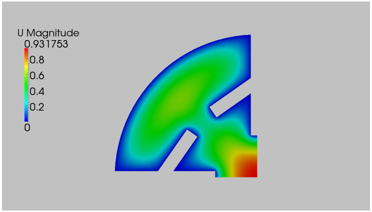


Lengthwise visualisation of mesh

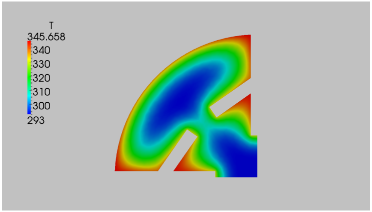
The 00036 mesh consists of 6215904 prism elements for the fluid region and 2796528 hexahedral elements for the solid region.

The 00036 model has two planes of symmetry and so we can reduce the mesh size to a quarter to lessen computational cost considerably. The model is solved using the boundary conditions and property calculations as Table 1. For different Reynolds numbers we change simply the mass flow rate (which translates to a inlet velocity change) and these are given explicitly in the spreadsheet provided.

In the 00036 model a circular tube has enhancements added. The size of the tube is such that the Hydraulic diameter remains as 1mm.



First wavelength coloured by temperature contour



First wavelength coloured by |U| contour

The strongest region of velocity lies in the center with pockets of low velocity in-between the enhancement fins. The mesh and data for this simulation are uploaded to the ftp for post processing and further simulations.

Mesh validation: friction factor

The friction factor f_d is a dimensionless constant (which can be expressed as a function of Reynolds number) which quantifies the resistance of the geometry to the flow relative to the flow conditions. If known it can be used to quickly calculate the pressure gradient using the DarcyWeisbach equation.

$$\Delta P = f_d \frac{L}{D} \frac{\rho V^2}{2} \tag{1}$$

For laminar flow the friction factor can be estimated in terms of the Reynolds number as

$$f_d = \frac{C}{Re} \tag{2}$$

Where C is a constant that depends on the shape of the cross section of the pipe. For a perfect cylinder C = 64 which can be derived from the analytical solution to Poiseuille flow. For a rectangular duct C depends on the aspect ratio. For a rectangular duct with sides of length a,b (b is the height and a is the width) C can be found in the below table

b/a	C
0	96
0.25	72.93
0.5	62.19
0.75	57.89
1	56.91

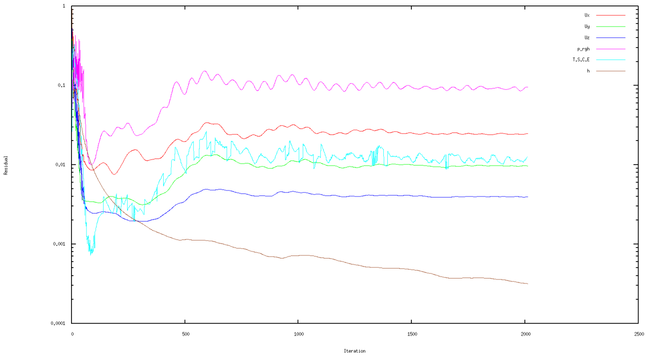
For a sanity check on the mesh resolution and simulation approach the friction factor was calculated on a mesh of the same resolution in the cross sectional plane and lengthwise direction for idealised cases. For these cases the friction factor is known and easily available.

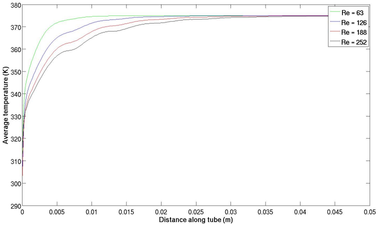
Model	Reynolds number	Calculated friction factor	Theoretical friction factor	Error (%)
cylinder	202	0.326	0.318	2.67
wavy3	163	0.354	0.349	1.39
wavy17	62.9	1.16	1.16	0
wavy33	78.86	0.943	0.925	1.97

The table shows results from the CFD on straight pipes with cross sections the same as the proposed wavy models and suggests a good quality mesh for providing accurate data. Note that the Reynolds number selection seems rather arbitrary but they all equate to the same mass flow rate for each model. Ideally a better sanity check would be to compare friction factor for the wavy models against experimental data. This can be easily done once the experimental results are available.

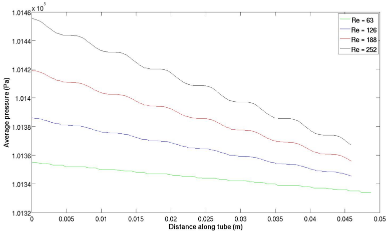
For the wavy3 design the solver failed to converge for Reynolds numbers 300 and above. The oscillating residuals suggest that the actual solution is transient in nature and can not be captured by a steady state solver. Transient simulations have a significantly increased computational cost and thus were not a part of this project.

The wavy17 model failed to converge for Reynolds number 345. It is possible that the onset of unsteady behaviour can be predicted by a function of Reynolds number and curvature. Understanding this in more detail would provide knowledge of what flow conditions it is possible to run a steady state solver and avoid unnecessary waste of computing time.





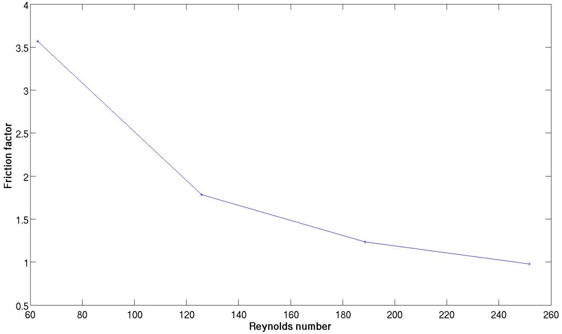
Plot of average temperature across tube at various Reynolds numbers



Plot of average pressure across tube at various Reynolds numbers

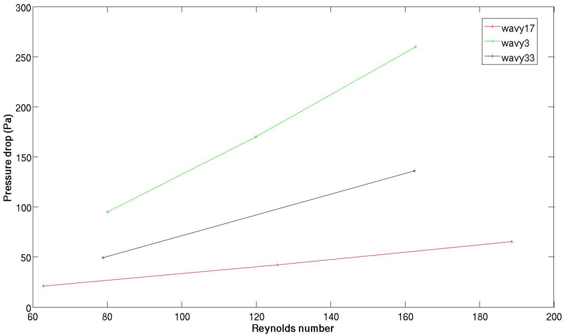
At higher mass flow rates (hence higher Reynolds numbers) we see the gradient of the pressure curve increasing with the curve with increasingly more visible waviness in the average pressure. The heat transfer is slower at higher Reynolds numbers with increasingly more visible waviness in the average temperature. With this data metrics of performance relevant to heat exchange (Friction factors and Colburn j factors for example) can be obtained to assess performance of a given model.

Example: Friction factor calculation wavy17



For the friction factor of the wavy17 model subject to heat transfer the friction factor is a non linear function of Reynolds numbers even at low Reynolds numbers. This is because the heat transfer rate has a non linear relationship with the flow conditions. Using this approach obtaining the friction factors for a tube design would mean having access to pressure drop data for a given model using the DarcyWeisbach equation.

Pressure drop over wavy models



For the three models we see that the wavy3 model, with the smallest hydraulic diameter and largest wave density has a higher pressure drop associated with it. As we increase the hydraulic diameter and decrease the wave density we see a reduction in the associated pressure drop at each Reynold number. Further calculations to see how these trends continue will allow for decisions based on the expected Reynolds number of the individual tubes in the context of a fixed volume heat exchanger.

Conclusions

- The wavy3 model, with high wave density, experiences separation even at lower Reynolds numbers which reduces the effective channel of the fluid flow resulting in higher velocities there. This separation and higher velocity flow results impedes the heat transfer because of the fluids exposure to the heated boundary is reduced. The higher fin density may cause unsteady behaviour at lower Reynolds numbers which will affect the modelling approach in future investigations.
- Under an unsteady regime the vortices generated by the shear layer after separation may break off and interact more with the bulk flow. This may lead to an increase in heat transfer with an extra penalty of pressure drop.
- The wavy33/wavy17 models with lower fin density does not experience separation at comparative Reynolds numbers to wavy3. Areas of high vorticity at 0.25/0.75 increments of the wavelength may enhance the heat transfer.
- The friction factor of these models when subjugated to heat transfer is a non linear function of Reynolds number even in laminar flows. As opposed to the isothermal case where the friction factor is a linear function of Reynolds number when the flow is laminar.
- The data in this report are from low Reynolds number flows. In higher Reynolds number flows more interesting behaviour such as shedding of vortices will have an influence on the pressure drop and heat transfer rate but will require more computationally demanding simulations.

Data on the FTP

	model	# simulations
heat transfer		
	wavy 3 straight	1
	wavy 17 straight	1
	wavy 3	3
	wavy 17	4
	wavy 33	4
	00036	1
	cylinder	2
isothermal		
	wavy 3	1
	wavy 3 straight	1
	wavy 17	1
	wavy 17 straight	1
	cylinder	1

The table shows the case data, which include mesh and simulation set up, for the different models. The breakdown of the flow conditions for models with numerous simulations will be detailed in a spreadsheet that will be included.