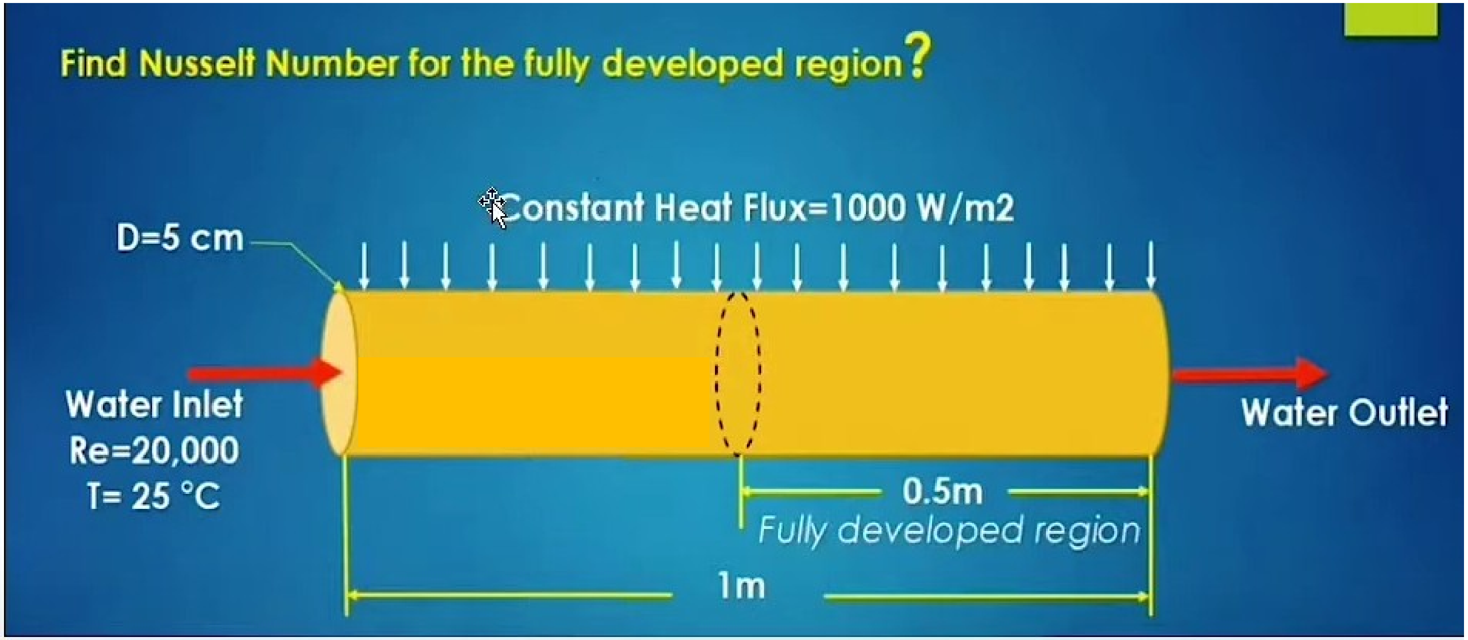
A fundamental heat transfer study using OpenFOAM



Properties of saturated water

Temp. T, °C	Density ρ, kg/m3	Specific Heat cp, J/kg·K	Thermal Conductivity k, W/m·K	Dynamic Viscosity μ, kg/m·s
25	997.0	4180	0.607	0.891×10^{-3}

https://www.youtube.com/watch?v=9vhwIYab7qE

Here two cases are studied using OpenFOAM v2406:
1- Constant heat flux
2- Constant surface temperature

Abdurrahman Imren

Constant Heat Flux

Re number is input. Entrance length correlation for turbulent flows is

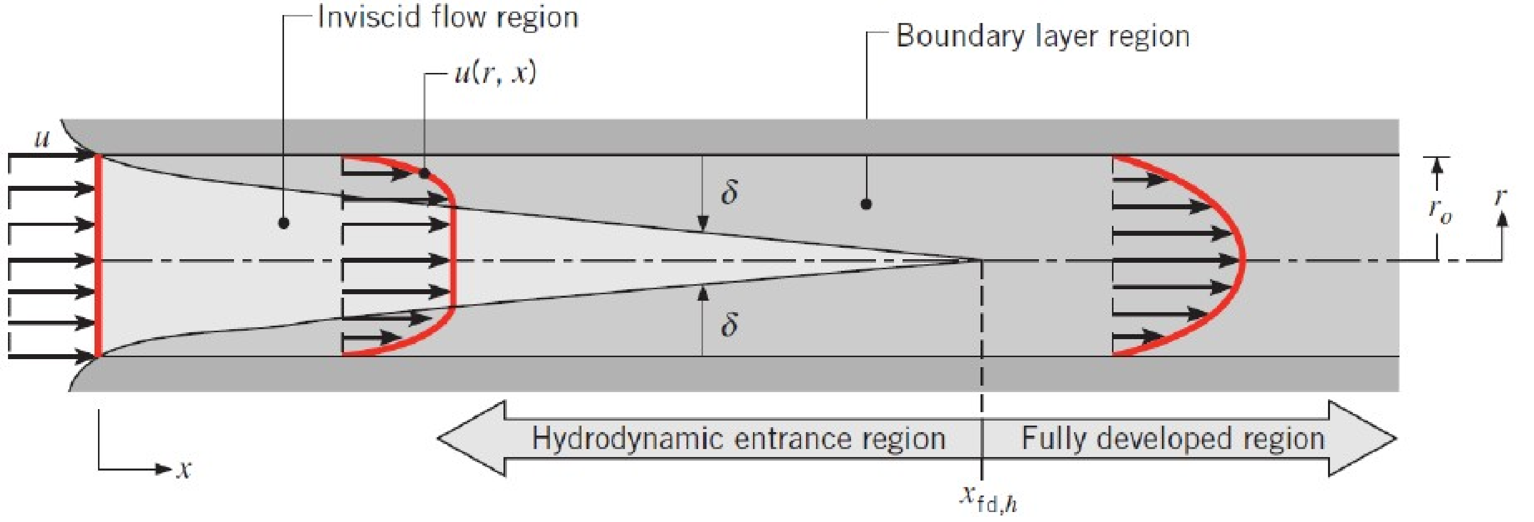
$$x_{fd,h-t} \simeq 10\,D = 0.5\,m.$$

This is the length to split pipe wall surface in two in *blockMeshDict.*

U: Using *Re* and given water properties at 25 C^o, inlet $U = 0.35747\,m/s$. *noSlip* BC is on the walls. Outlet patch is set to *zeroGradient*.

T: *T* inlet is 298.15 *K*. *ExternalWallHeatFluxTemperature* BC is selected to apply a constant heat flux (1000 W/m^2) on the pipe walls. Outlet is again *zeroGradient*.

p: For outlet pressure, *p* is at 101325 *Pa*. Inlet and wall patches are set to *zeroGradient*.



From notes of JM Meyers ME-144 Heat Transfer

Constant Heat Flux

Three RANS turbulence models will be tested on y^{+}*~3* and y^{+}*~40 meshes*:

- *kEpsilon*
- *kOmega and kOmegaSST*

First, we have to do some preliminary calculations:

For fully developed turbulent flow, Nusselt number can be predicted using Dittus-Boelter correlation

$$Nu_D = 0.023\, Re_D^{4/5}\, Pr^n$$

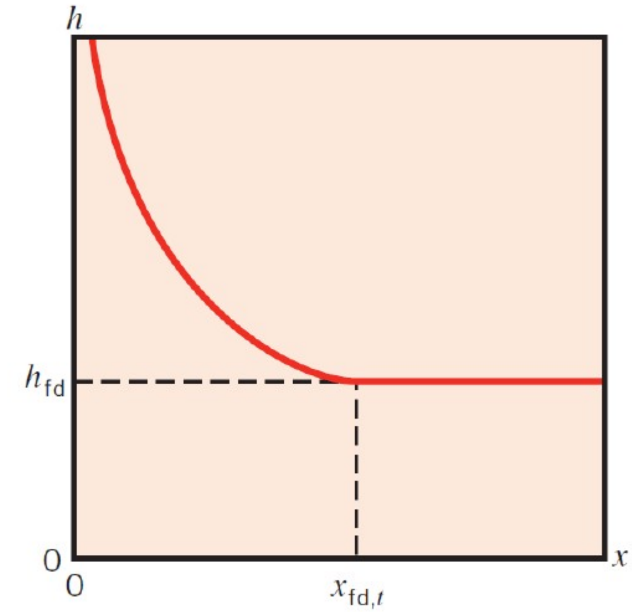
where *n=0.4* is for heating and *n*=0.3 for cooling.

$$Nu_D = 0.023(20000)^{4/5}(6.13)^{0.4} = 131.13$$

Then, heat transfer coefficient is found as

$$h = \frac{Nu_D k_f}{D_h} = 1591\, W/m^2 - K$$

where k_f is thermal conductivity of water and D_h is hydraulic diameter.



From notes of JM Meyers ME-144 Heat Transfer

Dittus-Boelter correlation range

$$\begin{bmatrix} 0.6 \lesssim Pr \lesssim 160 \\ Re_D \gtrsim 10{,}000 \\ \dfrac{L}{D} \gtrsim 10 \end{bmatrix}$$

Constant Heat Flux

Mean temperature variation along the pipe can be found from energy balance equation applied on an infinitesimal control volume element:

$$\frac{dT_m}{dx} = \frac{q\,P}{\dot{m}\,C_p}$$

where P is perimeter. Since RHS is constant, T_m can be integrated as:

$$T_m(x) = T_{m,inlet} + \frac{q\,P}{\dot{m}\,C_p}\,x$$

To calculate surface temperature T_s, Newton's Law of cooling is applied

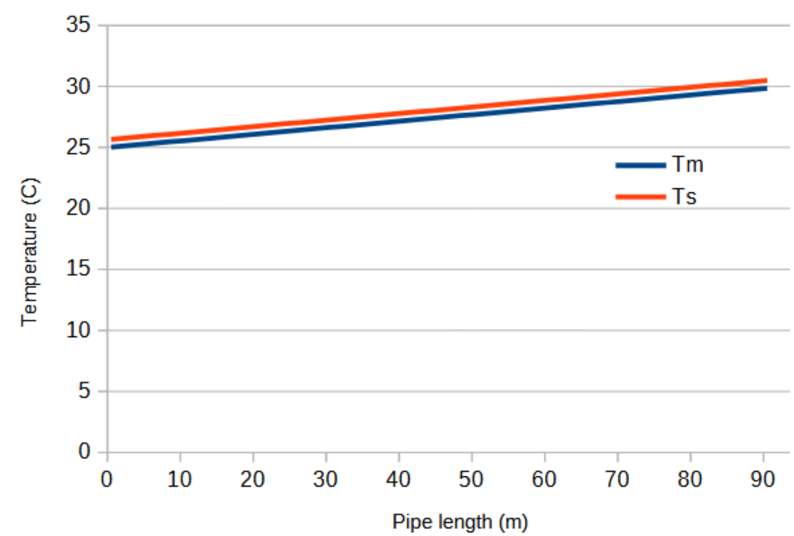
$$q = h(T_s - T_m) = constant\,.$$

h is also constant along the fully developed portion of the pipe. Then differentiation gives:

$$\frac{dT_s}{dx} = \frac{dT_m}{dx} \Rightarrow T_s(x) = T_m(x) + \frac{q}{h}$$

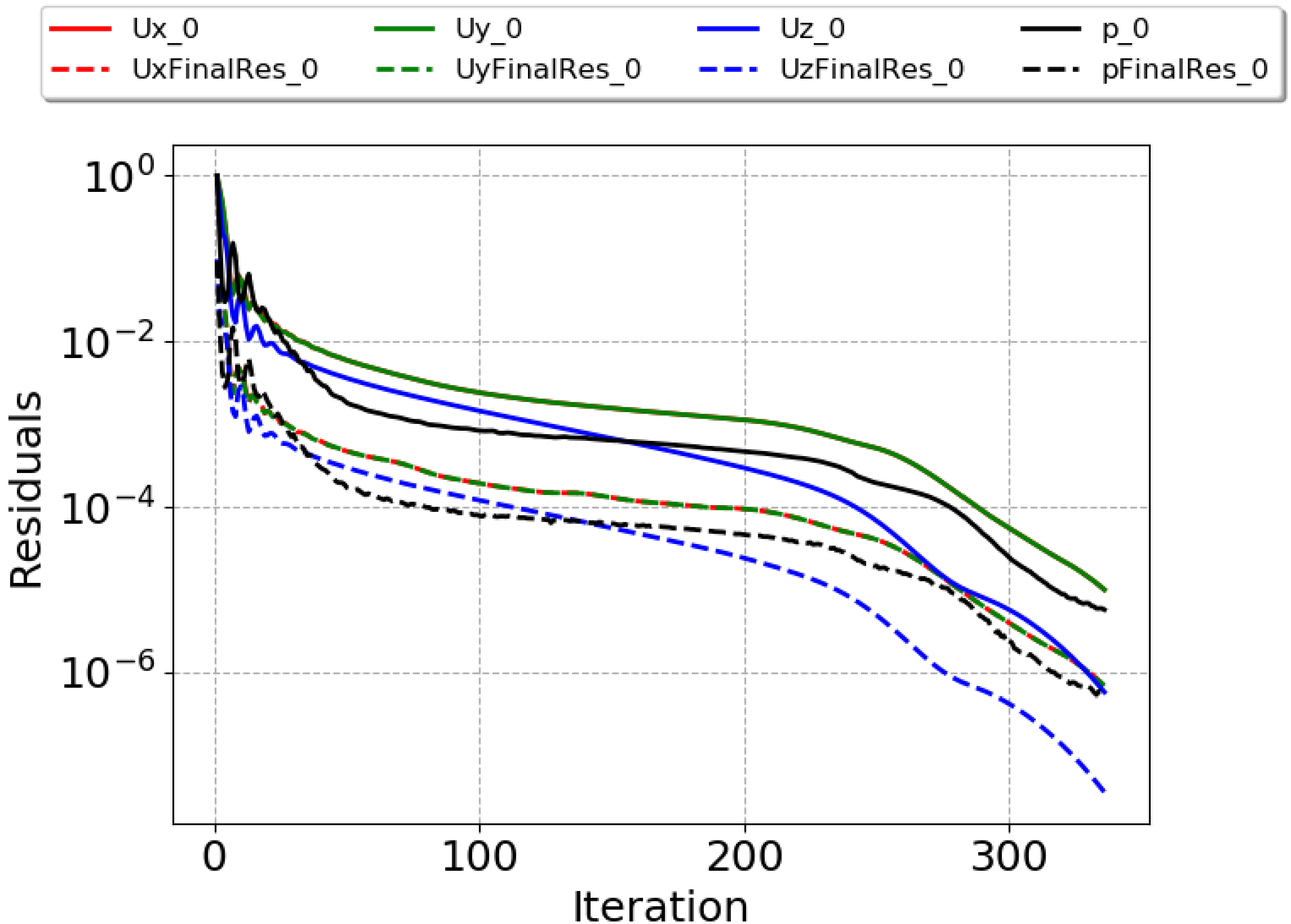
$$T_m(L) = 298.15 + 0.0537\,L = 298.2037\,K$$

$$T_s(L) = 298.2037 + 1000/1591 = 298.832\,K$$



Constant Heat Flux

Steady state simulation (*rhoSimpleFoam*) – e.g. *kOmegaSST*-y^+~3 residual plot



Constant Heat Flux – CFD Results

		$y^+ \sim 3$		
	Correlation	**kEpsilon**	**kOmega**	**kOmegaSST**
dP (Pa)	33	64	40	38
$T_{m,outlet}$ *(K)*	298.204	298.211	298.218	298.22
$T_{s,ave}$ *(K)*	298.82	298.5	298.786	298.813
$\bar{h}$ *(W/m²-K)*	1591	2840	1572	1509

		$y^+ \sim 40$		
	Correlation	**kEpsilon**	**kOmega**	**kOmegaSST**
dP (Pa)	33	37	38	36
$T_{m,outlet}$ *(K)*	298.204	298.209	298.208	298.209
$T_{s,ave}$ *(K)*	298.82	298.79	298.774	298.813
$\bar{h}$ *(W/m²-K)*	1591	1569	1604	1507

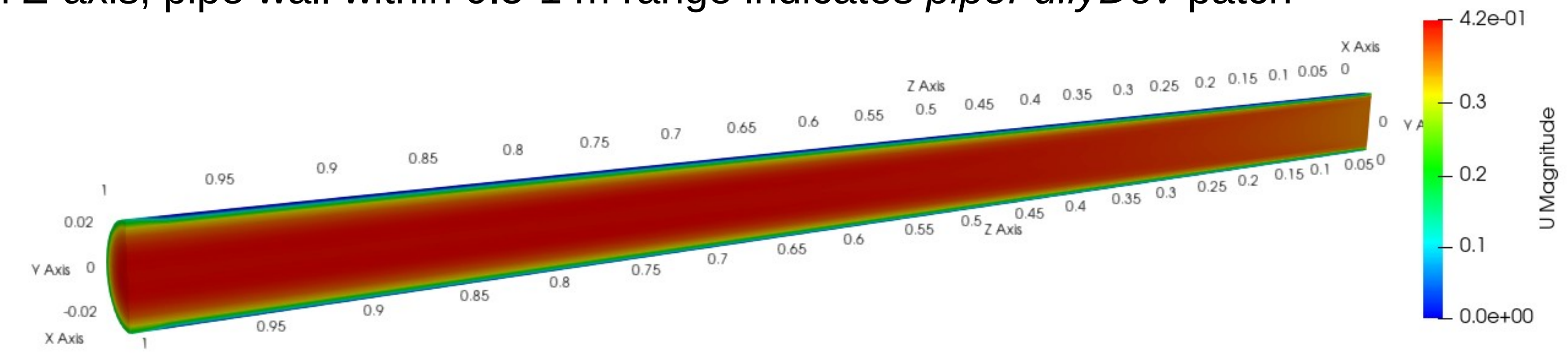
Ts,ave = 0.5 (Ts(L/2) + Ts(L))=298.82 K

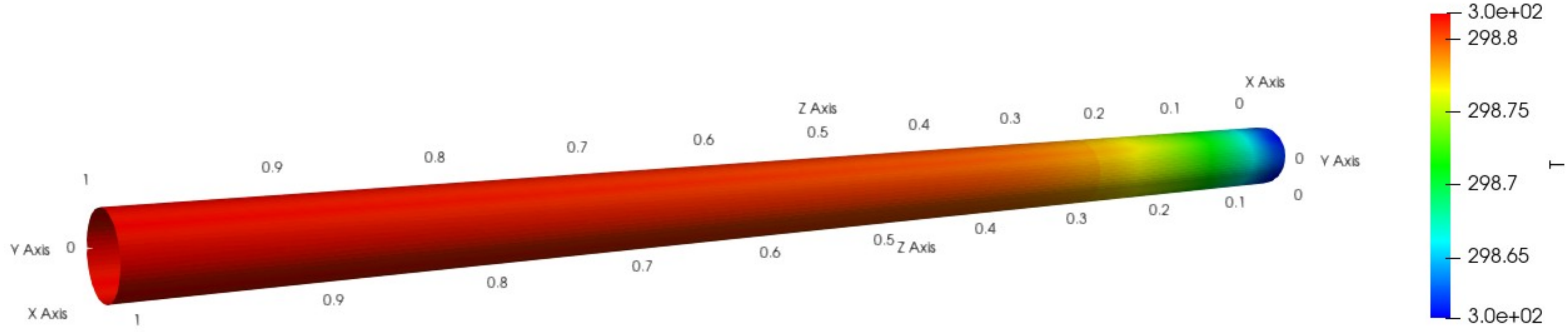
Recall $h = \frac{q}{T_s - T_{ref}}$. Temperature difference is small and constant *q* is relatively large, i.e. small difference in temperature can make big difference in *h*.

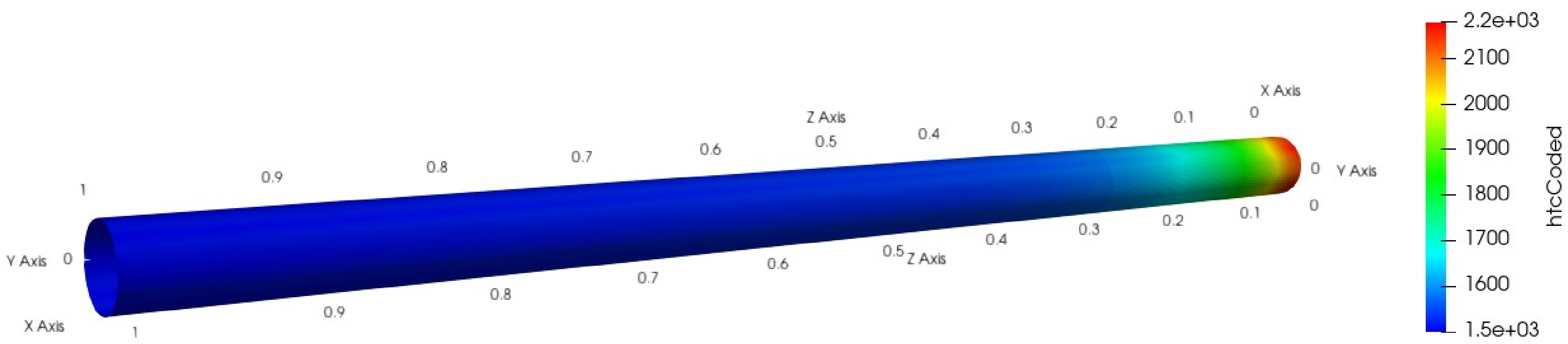
Since outlet temperature did not significantly change, T_{ref} was set to 298.15 C^o.

Constant Heat Flux – kOmegaSST y^+~40

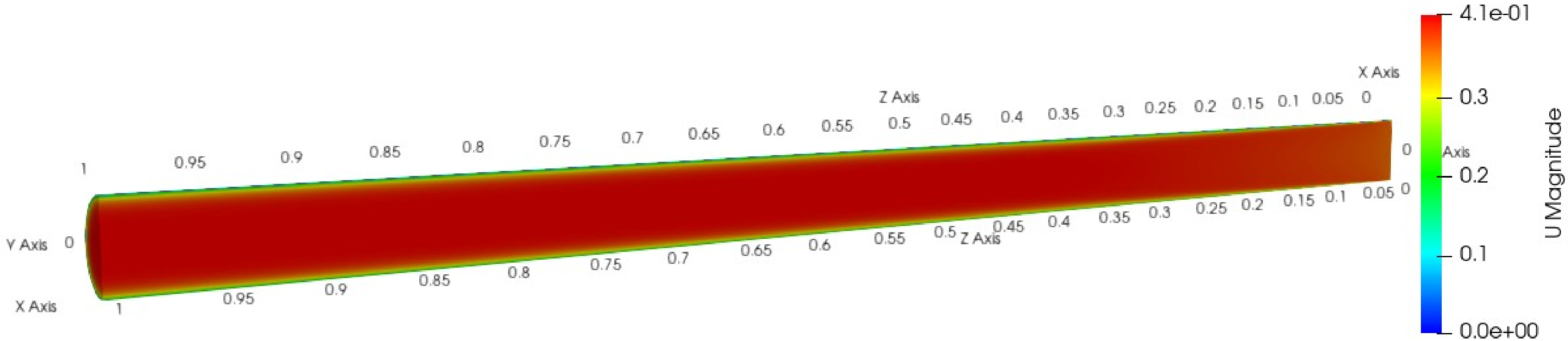
On Z-axis, pipe wall within 0.5-1 m range indicates *pipeFullyDev* patch

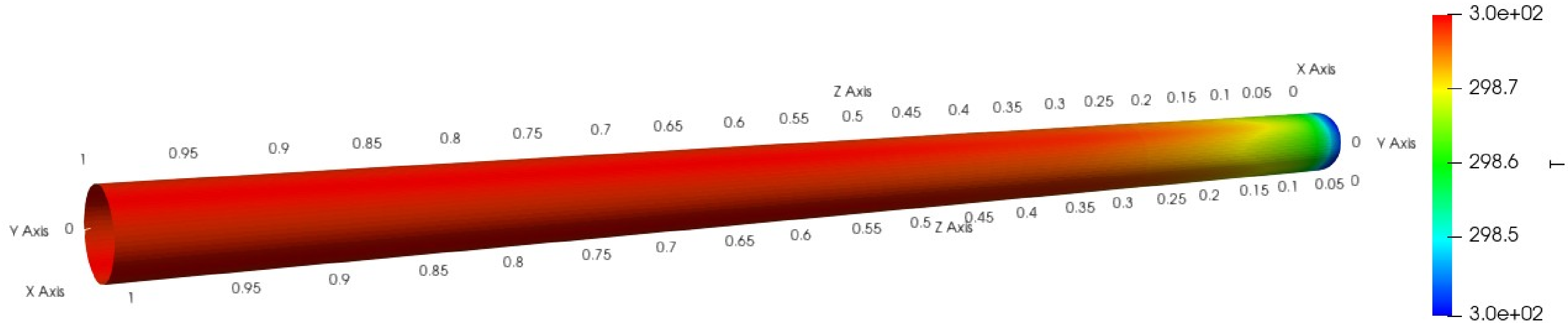


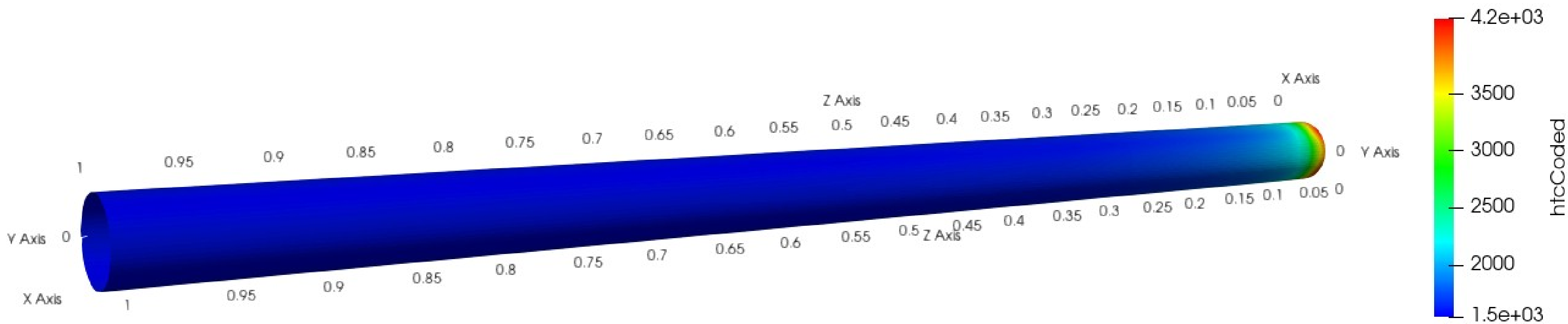




Constant Heat Flux – kOmegaSST y^+~3

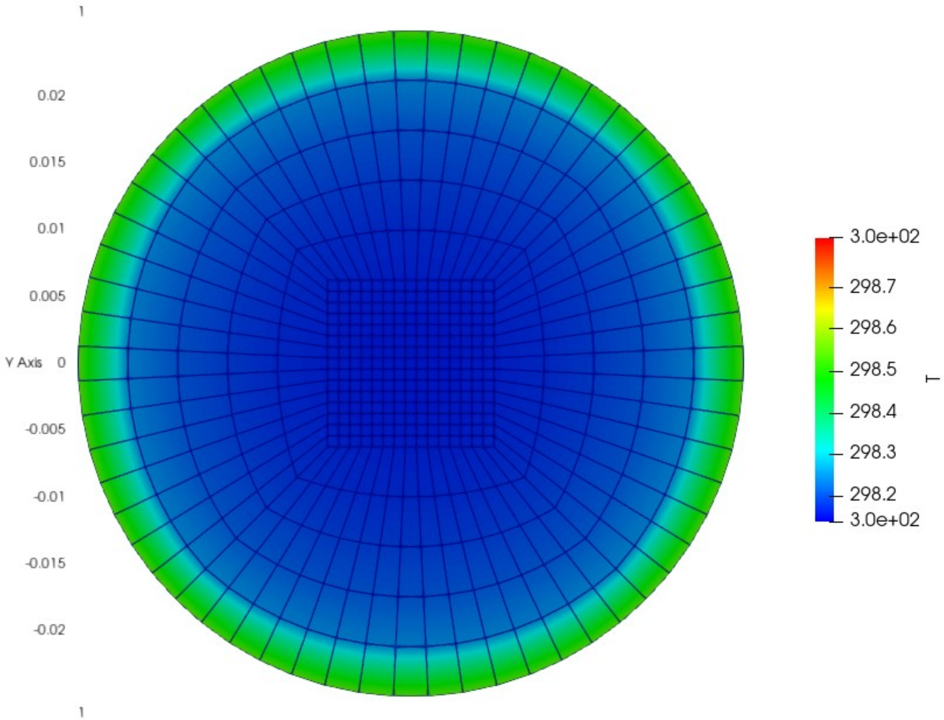


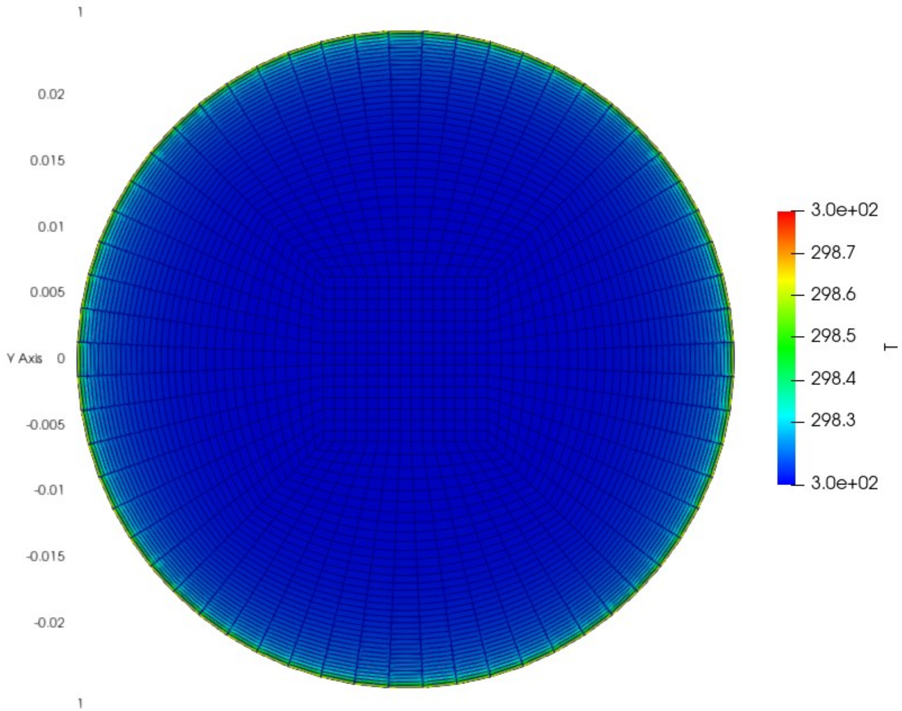




Constant Heat Flux – kOmegaSST y^+~3 and y^+~40

Computational expense brings better profile resolution





Constant Surface Temperature

Constant Surface Temperature

Mean temperature variation along the pipe can be found from energy balance equation applied on an infinitesimal control volume element:

$$\frac{dT_m}{dx} = \frac{q P}{\dot{m} C_p}$$

where P is perimeter. Since T_s is constant, $\Delta T = T_s - T_m$ is defined. ODE solution is

$$T_m(x) = T_s - (T_s - T_{m,inlet}) e^{-\frac{P \bar{h}}{\dot{m} C_p} x}$$

h(x) is integrated. Therefore, average h along the entire pipe has to be considered

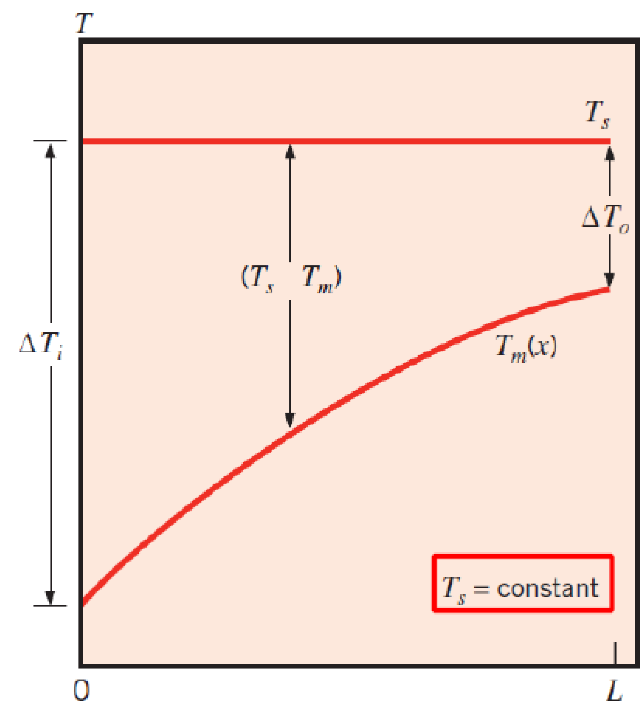
Let T_s be 100 C^o (fixed, uniform). Average T_m needs to be predicted. As a first guess, average of inlet and outlet temperatures can be taken. There, $T_{m,outlet}$ is set to wall surface temperature ($T_{m,outlet} = T_s$):

$$T_{m,ave} = 1/2 (T_s + T_{m,inlet}) = 62.5 C.$$

Then, properties of water are updated with this new *ref* temperature. Here, for simplicity, 60 C^o input was used. Dittus-Boelter correlation gives Nu = 165 and h=2158 W/m^2-K.

$$T_m(L) = 100 - (100 - 25) 0.891 = 33.2 C$$

Picking $\Delta T = T_s - T_m = 0$ helped us find the neighborhood of $T_{m,outlet}$. Second iteration is needed.



Constant Surface Temperature

In the second iteration, we use $T_m(L) = 33.2\ C^o$ from the first iteration.

$$T_{m,ave} = 1/2\left(33.2 + 25\right) = 29.1\,C\,.$$

Using new *ref* temperature, Dittus-Boelter correlation gives $Nu = 136$ and $\bar{h}$=1679 W/m^2-K at 30 C^0.

$$T_m\left(L\right) = 100 - \left(100 - 25\right)0.9138 = 31.465\,C = 304.62\,K$$

For simplicity (or available table data), we stop iteration here and expect to have consistent results with those of CFD.

$$T_{ref} = T_{m,ave} = 1/2\left(31.465 + 25\right) = 28.235\,C = 301.385\,K\,.$$

Constant Surface Temperature

		$y^+ \sim 3$		
	Correlation	**kEpsilon**	**kOmega**	**kOmegaSST**
dP (Pa)	33	64	40	38
$T_{m,outlet}$ *(K)*	304.62	311.68	306.62	306.42
$\overline{h}$ $(W/m^2\text{-}K)$	1679	3111.7	1764.3	1669.58

		$y^+ \sim 40$		
	Correlation	**kEpsilon**	**kOmega**	**kOmegaSST**
dP (Pa)	33	37	38	36
$T_{m,outlet}$ *(K)*	304.62	305.31	305.38	305.15
$\overline{h}$ $(W/m^2\text{-}K)$	1679	1706.9	1749.3	1639.5

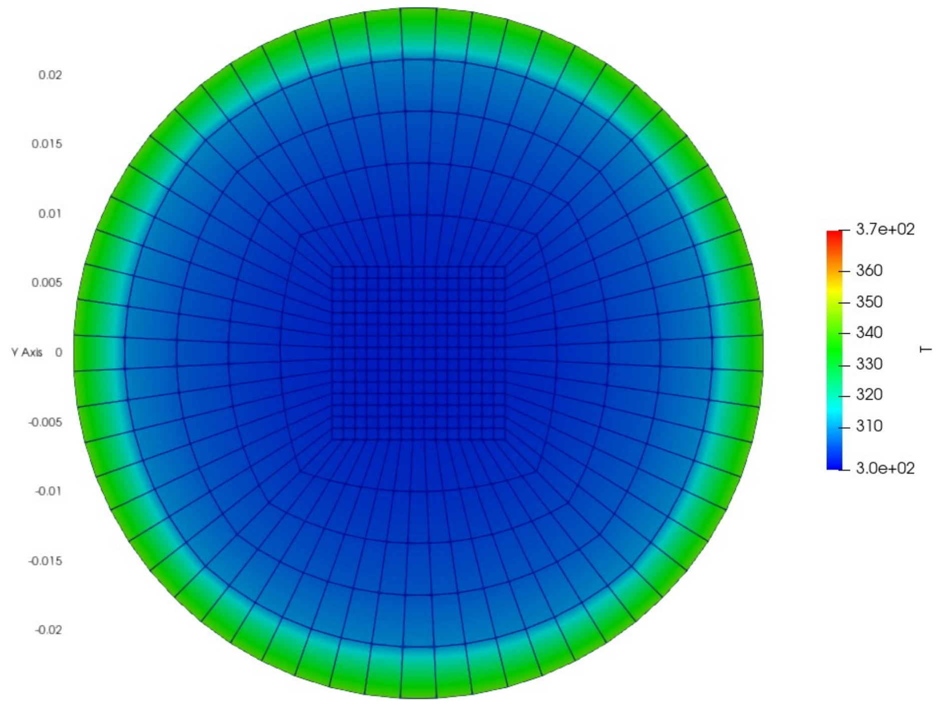
In CFD calculations, T_{ref} = 301.385 K was used. $\overline{h}$ is average of *pipeEntry* and *pipeFullyDev* patches since ODE integration is done along the entire pipe. However, in constant heat flux case, fully developed h (~constant) is taken so that T_s (x) can be calculated.

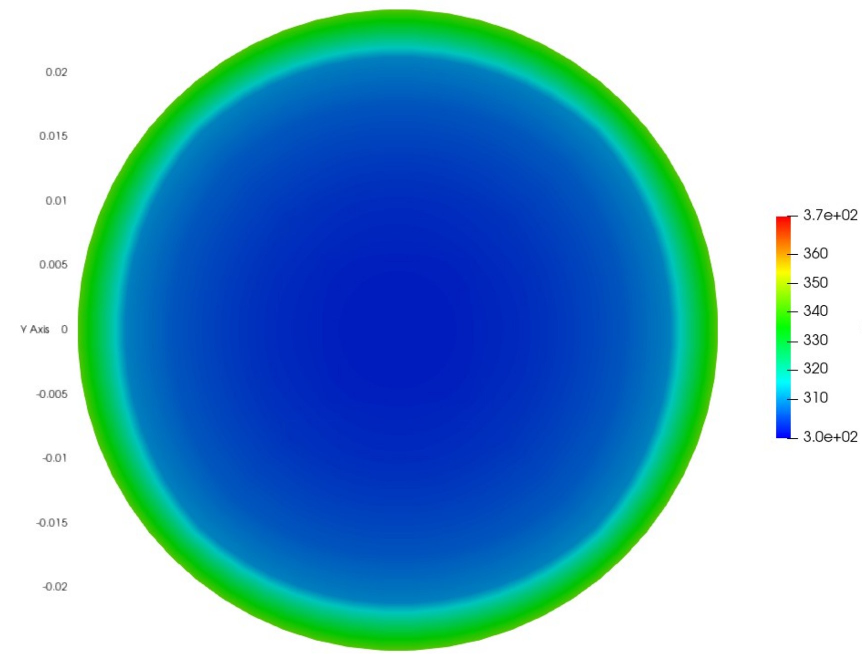
Results for T_{ref} = 298.15 K were also printed in the log files.

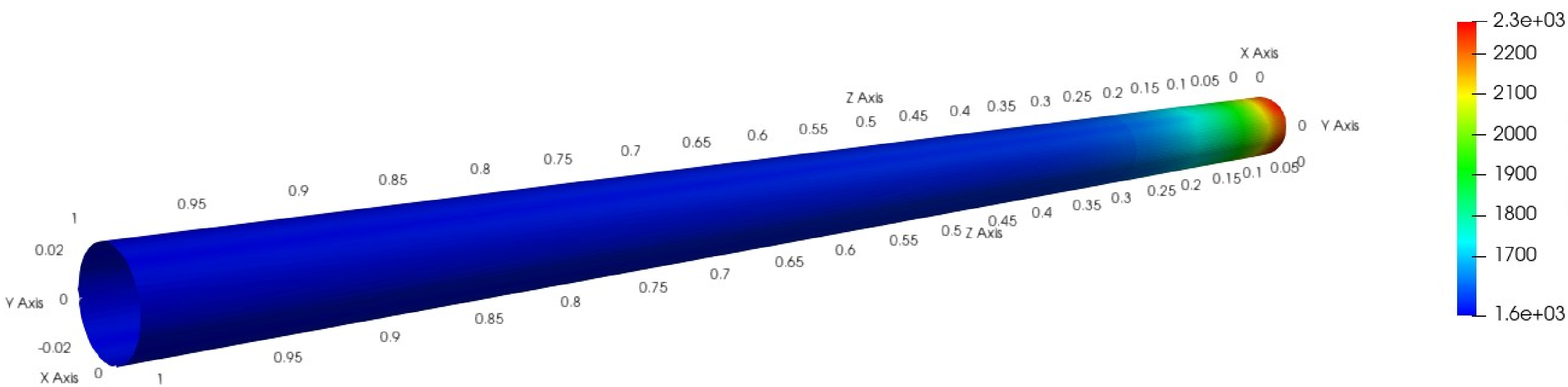
One major thing we observe is that refining near wall mesh region does not help if a high-Re turbulence model is chosen.

Constant Surface Temperature

komegaSST - **y^+ ~ 40**







Constant Surface Temperature

KomegaSST - **y^+ ~ 3:** Profile is resolved