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School on Physics, Technology and Applications of Accelerator Driven Systems (ADS)

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Thermal Hydraulics of Heavy Liquid Metal Target for ADS. Part II

Polepalle SATYAMURTHY

BARC - ADS Target Development Section
Beam Technology Development Group
400085 Mumbai
India

Thermal-hydraulics of ADS target - Lecture-2

P. Satyamurthy

ADS Target development Section,

Bhabha Atomic Research Centre

Mumbai-400085, India

Contents of Lecture -2:

1) Pumping methods:
   -1) Buoyancy
   2) Mechanical pumping
   3) Gas driven pumping

2) Pressure drop calculations

Contents of Lecture -2: cont.

3) **CFD analysis of flow in the spallation and window region:**

Flow modeling

Governing equations

Boundary and inlet conditions

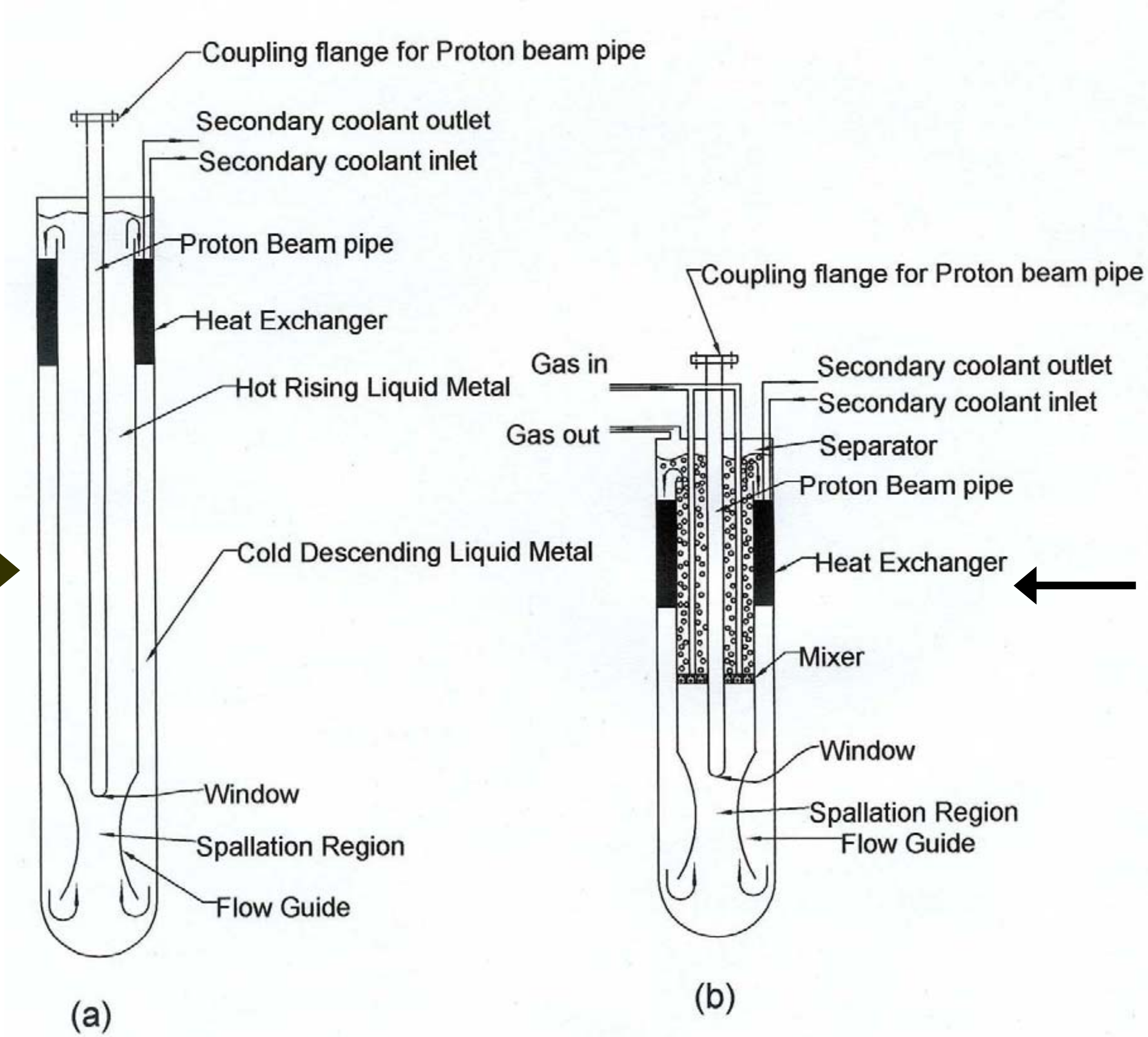
Heat Deposition data from FLUKA

Numerical solution methods

Flow and Geometric Optimization of Target configuration

Issues related to flow analysis under abnormal conditions

Window Type Target loops-Various Circulating Methods



Buoyancy Driven

Gas-driven

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Window Type Target loops-Various Circulating Methods

- Conventional Pump Driven loop
  - Mechanical Pump
  - Electromagnetic Pump (low efficiency: ~ 3% Due to low electrical conductivity $\sim 10^6$ mho/m)
- Buoyancy Driven Loop
- Gas driven Loop

Pressure head

1) Buoyancy Loop

$$\Delta P_{Buoy} = \beta \rho_{cold} \Delta T g h$$

β=Volumetric Expansion coefficient (1/K)~1.24×10^{-4} for LBE

2) Gas Driven Loop

$\Delta P_{head} = \alpha_{ave} \rho_{cold} .g.h$ + Buoyancy head

$\alpha_{ave} \sim 0.25$

Pressure losses in the Loop

$$\Delta P_{loss} = \frac{1}{2}\left[\sum_i f_l \frac{L_i}{D_i}\rho_l \bar{v}_i^{\,2} + \sum_i K_i \rho_{li} \bar{v}_i^{\,2} + \Phi_{lo}^2 f_l \frac{L_{two-phase}}{D_{two-phase}} \rho_{li} \bar{v}_{lo}^2 \right]$$

$$\propto v^2$$

$$\propto m_l^2$$

$$\frac{1}{\sqrt{f_l}} = -2.0 \log\left[\frac{\varepsilon}{3.7d} + \frac{2.51}{R_e \sqrt{f_l}}\right]$$

Additional term for gas driven systems

L_i = pipe length in the i^{th} region, ρ_l = Density of liquid in the region, f_{lo} =friction factor, $v^2{}_{lo}$= average liquid velocity, D= Hydraulic diameter, m_l=liquid mass flow rate

Φ_{lo}^2 **=Two-phase multiplication factor**

Two-phase flow-Pressure Drop Calculations-
Some more details

$$\phi_{lo}^2 = (1-X)^2 + X^2\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{f_g}{f_l}\right) + \left(\frac{3.24\left(X^{0.78}\right)(1-X)^{0.24}\left(\frac{\rho_l}{\rho_g}\right)^{0.91}\left(\frac{\mu_g}{\mu_l}\right)^{0.19}\left(1-\frac{\mu_g}{\mu_l}\right)^{0.7}}{F_r^{0.045} w_e^{0.035}}\right)$$

$$\rho_t = \frac{\rho_l \rho_g}{X\rho_l + (1-X)\rho_g} \qquad G = \frac{\dot{m}_l + \dot{m}_g}{A} \qquad X = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l} \qquad W_e = \frac{G^2 D}{\rho_t \Sigma_l}$$

$$F_r = \frac{G^2}{gD\rho_t^2}$$

Σ_l = surface tension of liquid metal,

W_e = Weber number

F_r = Froude number

CFD analysis of flow in the spallation and window region

Why do we require CFD (Computational Fluid Dynamics) analysis?

- The spallation heat is distributed in the target and window.
- The temperature field in the window and target should be accurately known to ensure there is no excess temperature (than the designed one) in the entire region
- To know the temperature field we require to know the velocity field accurately
- Detailed temperature in the window and other components are needed for thermo-mechanical stress calculations
- For Target geometry and flow optimization

Characteristic of the LBE Flow

- Flow is turbulent
- Strictly 3D flow but can be approximated 2D axi-symmetric flow
- Buoyancy effects have to be taken into account
- Low Prandtl number (due to high thermal conductivity)
- Volumetric heat deposition and surface heat transfer

Basic Fluid equations

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{u} \right) = 0$$

Momentum equation

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \bullet \left(\rho \vec{u} \vec{u} \right) = -\nabla P + \nabla \bullet \overleftrightarrow{\tau} + \rho \vec{g}$$

$$\overleftrightarrow{\tau} = \mu \left[\left(\nabla \vec{u} + \nabla \vec{u}^{T} \right) - \frac{2}{3} \nabla \bullet \vec{u} I \right]$$

Basic Fluid equations - cont

Energy Equation

$$\frac{\partial(\rho E)}{\partial t} = \nabla \bullet (\vec{u}(\rho E + p)) = -\nabla \bullet \vec{q} + s - \nabla \bullet (\vec{u} \bullet \overleftrightarrow{\tau})$$

$$E = \text{int energy} + \text{kinetic energy per unit mass}$$

$$\vec{\mathrm{q}} = \text{heat flux}\,;\,\mathrm{s} = \text{heat deposited per unit volume}$$

Simplification of flow equations for CFD analysis

- **Flow is incompressible except for variation in the density due to temperature (Boussinesq approximation)**
- **Flow is Turbulent**

$$\vec{u} \Rightarrow \vec{u}\ (\text{mean value}) + \vec{u}'(\text{fluctuating value})$$

$$\vec{\vec{\tau}} = \mu\left[\left(\nabla\vec{u} + \nabla\vec{u}^{T}\right) - \frac{2}{3}\nabla \bullet \vec{u}I\right] - \rho\overline{\vec{u}'\vec{u}'}$$

- **Similarly for other variables**

Eddy Viscosity Concept

- Boussinesq (1877) proposed this concept

- Turbulent stresses are proportional to mean velocity gradients

- $$-\rho\overline{\vec{u}'\vec{u}'} = \mu_t\left[\nabla\vec{u} + \nabla\vec{u}^{\,T}\right] - \frac{2}{3}kI$$

$$\mu_t \propto v_0 l_0 \quad \text{where } v_0 = \text{velocity scale}$$

$$l_0 = \text{length scale}$$

K-ε Model

$$v_0 = \sqrt{k}$$

$$l_0 = \frac{k\sqrt{k}}{\varepsilon}$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

Flow Equations: Continuity & Momentum

u_r u_z are the components of velocity vector in the z and r directions, ρ is the density of the liquid metal.

p pressure, μ_e is effective viscosity, g_z acceleration due to gravity.

ρ_{ref} reference density corresponding to inlet density of the liquid metal

$$\frac{1}{r}\frac{\partial(\rho r u_r)}{\partial r}+\frac{\partial(\rho u_z)}{\partial z}=0$$

$$\frac{\partial \rho u_r}{\partial t}+\frac{1}{r}\frac{\partial(\rho r u_r u_r)}{\partial r}+\frac{\partial(\rho u_z u_r)}{\partial z}=-\frac{\partial p}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}\left(\mu_e r\frac{\partial u_r}{\partial r}\right)+\frac{\partial}{\partial z}\left(\mu_e\frac{\partial u_r}{\partial z}\right)-\mu_e\frac{u_r}{r^2}$$

$$\frac{\partial \rho u_z}{\partial t}+\frac{1}{r}\frac{\partial(\rho r u_r u_z)}{\partial r}+\frac{\partial(\rho u_z u_z)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}\left(\mu_e r\frac{\partial u_z}{\partial r}\right)+\frac{\partial}{\partial z}\left(\mu_e\frac{\partial u_z}{\partial z}\right)+(\rho_{ref}-\rho)g_z$$

Flow Equations: Energy and Turbulent Energy

C_p is specific heat at constant pressure,

T is time averaged temperature.

q_T volumetric heat generation

μ_m molecular viscosity

k_m molecular thermal conductivity

C_μ the turbulent model constant

k turbulent kinetic energy

$$\frac{\partial \rho C_p T}{\partial t} + \frac{1}{r}\frac{\partial\left(\rho C_p r u_r T\right)}{\partial r} + \frac{\partial\left(\rho C_p u_z T\right)}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_k \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\Gamma_k \frac{\partial T}{\partial z}\right) + q_T$$

$$\mu_e = \mu_m + \mu_t \qquad \mu_t = C_\mu \rho \frac{k^2}{\varepsilon} \qquad \Gamma_k = \left(k_m + \frac{\mu_t C_p}{\sigma_t}\right)$$

$$\frac{\partial \rho k}{\partial t} + \frac{1}{r}\frac{\partial\left(\rho r u_r k\right)}{\partial r} + \frac{\partial\left(\rho u_z k\right)}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial z}\right) + S_k + \frac{\beta\mu_t}{\sigma_t}\left(g_z \frac{\partial T}{\partial z}\right)$$

Flow Equations: Turbulent kinetic energy dissipation

σ_k **Prandtl no. for the turbulent kinetic energy.** β **coefficient of thermal expansion**

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{1}{r}\frac{\partial(\rho r u_r \varepsilon)}{\partial r} + \frac{\partial(\rho u_z \varepsilon)}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right) + S_\varepsilon + \frac{C_{1\varepsilon}\varepsilon}{k} B$$

$$S_\varepsilon = \frac{\varepsilon}{k}\left(C_{1\varepsilon} G - C_{2\varepsilon}\rho\varepsilon\right) \qquad S_k = G - \rho\varepsilon \qquad B = \frac{\beta\mu_t}{\sigma_t}\left(g_z \frac{\partial T}{\partial z}\right)$$

$$G = \mu_t \left\{ 2\left[\left(\frac{\partial u_r}{\partial r}\right)^2 + \left(\frac{\partial u_z}{\partial z}\right)^2 + \left(\frac{u_r}{r}\right)^2 \right] + \left(\frac{\partial u_z}{\partial r} + \frac{\partial u_r}{\partial z}\right)^2 \right\}$$

Inlet & Boundary conditions

- **Heat data from Fluka code**
- **Inlet velocity**
- **Inlet temperature**
- **Out let pressure**
- **Inlet Turbulent kinetic energy**
- **Inlet turbulent dissipation**
- **Inner wall and outer wall thermal condition (Adiabatic wall)**

CFD Analysis of a Typical Target

Target Parameters - 1

Proton Beam

- **Energy: 1GeV**
- **Current: 10 mA**
- **Profile: Parabolic**
- **Heat Deposited in Window ~ 55 kW**
- **Total Heat Deposited: ~ 6.5 MW**

Target Parameters -2

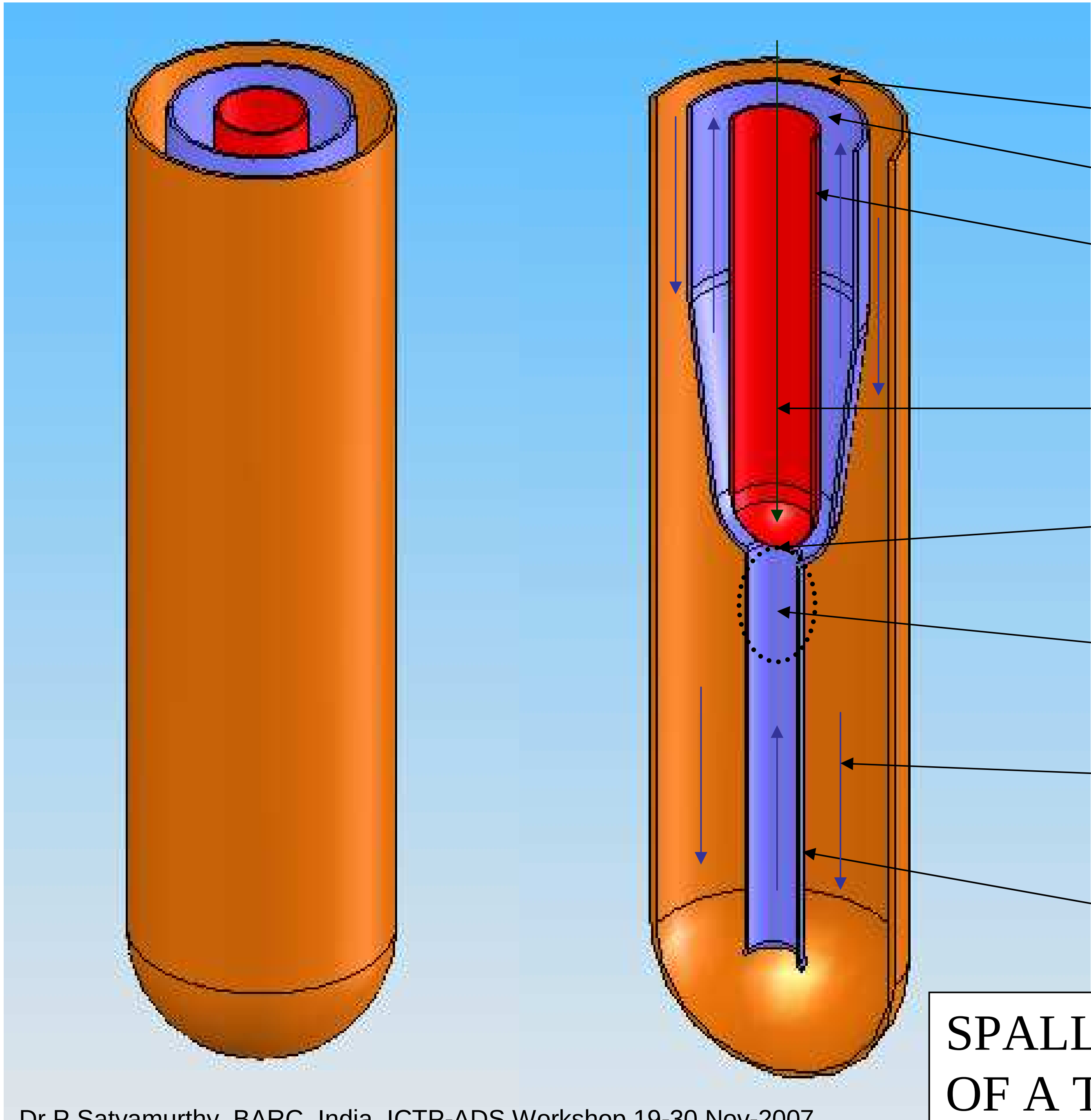
- **Window – T91**

(Ni:0.13,Cr:8.26,Mn:0.38,Mo:0.95,Si:0.43Ti:0.014, V:0.2,C:0.105,P:0.009,S:0.003,Nb:0.08,N:0055, Al:0.024,Cu:0.08,As:0.02,Sn:0.008,Fe:balance)

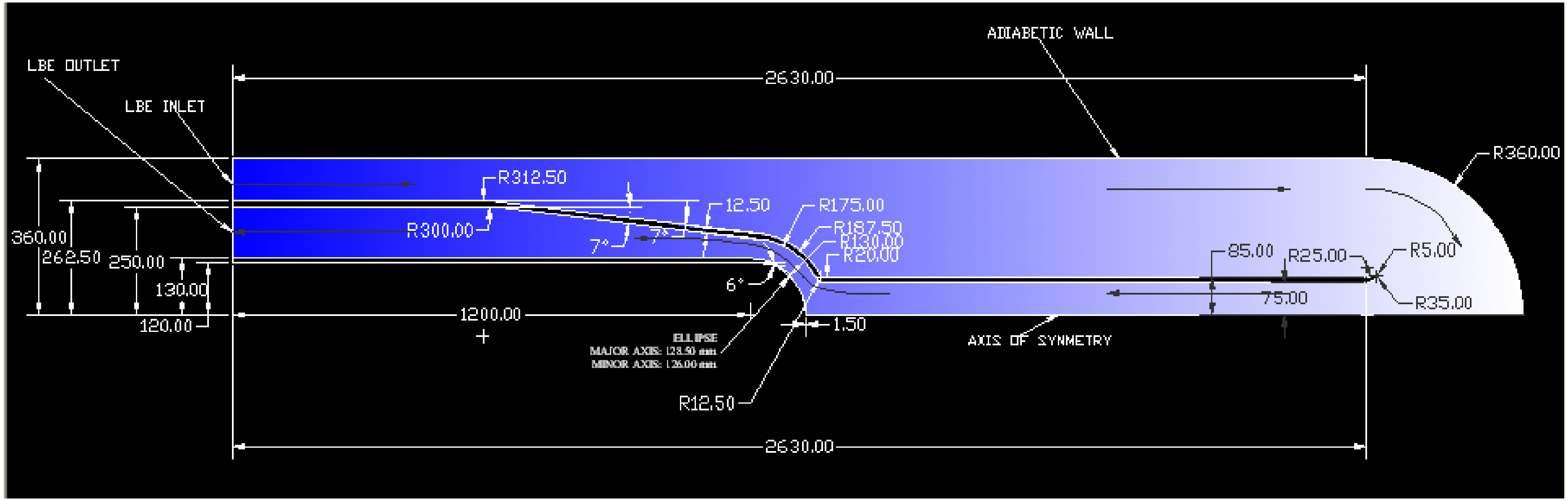
- **Other components – T91/316L**
- **Target – LBE**
- **Inlet temperature of LBE – 500 K**

Target Parameters - 3

- **Design Considerations**
  - Maximum Current Density< 50μA/cm^2
  - Maximum LBE flow rate anywhere in flow field < 2.0 m/s
  - Maximum LBE flow rate in riser and down comer < 0.2 m/s
  - Maximum Window Temperature < 873 K
  - Maximum Thermal Stresses < 400 MPa (Secondary Stresses)

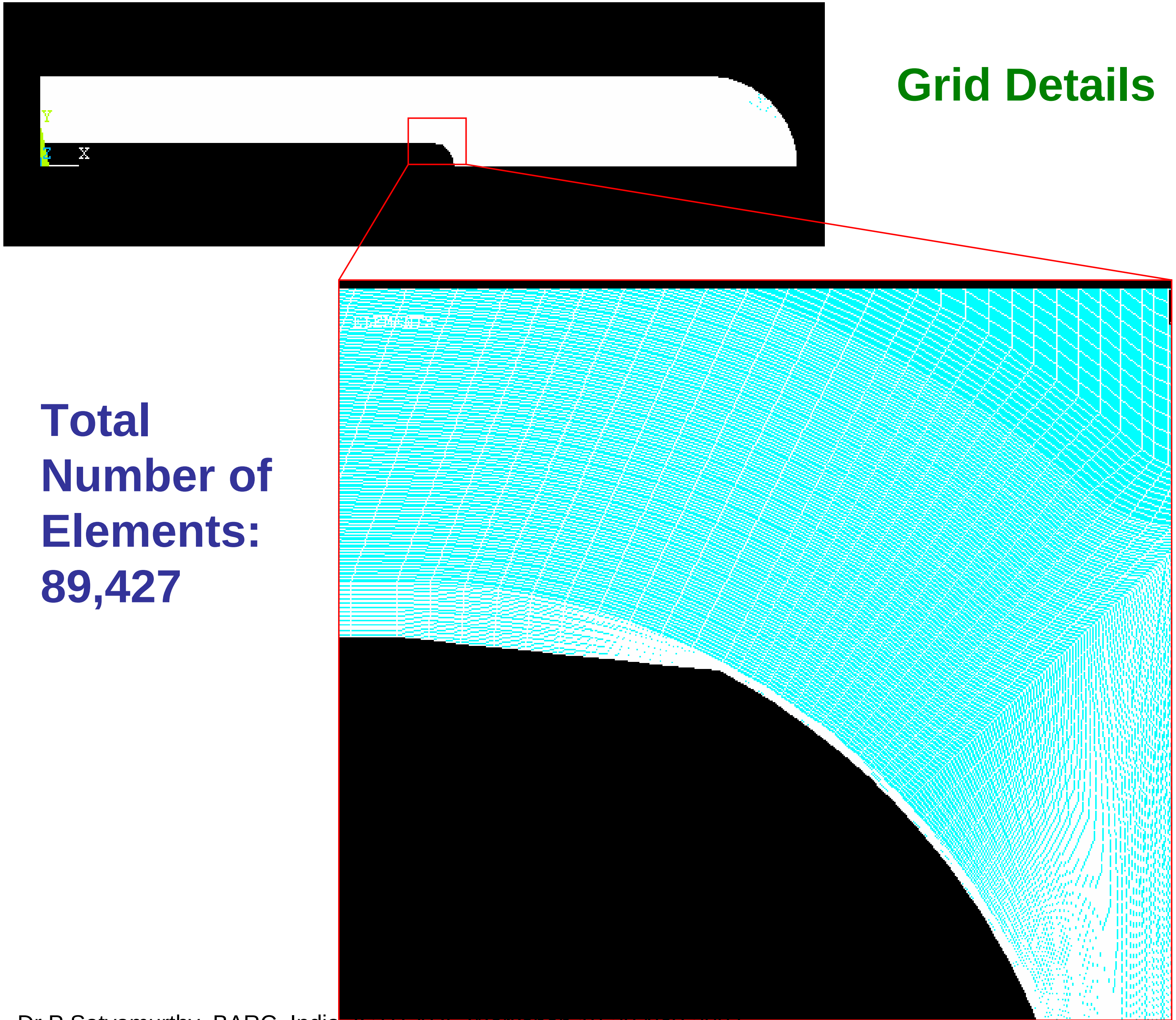


SPALLATION REGION OF A TYPICAL TARGET



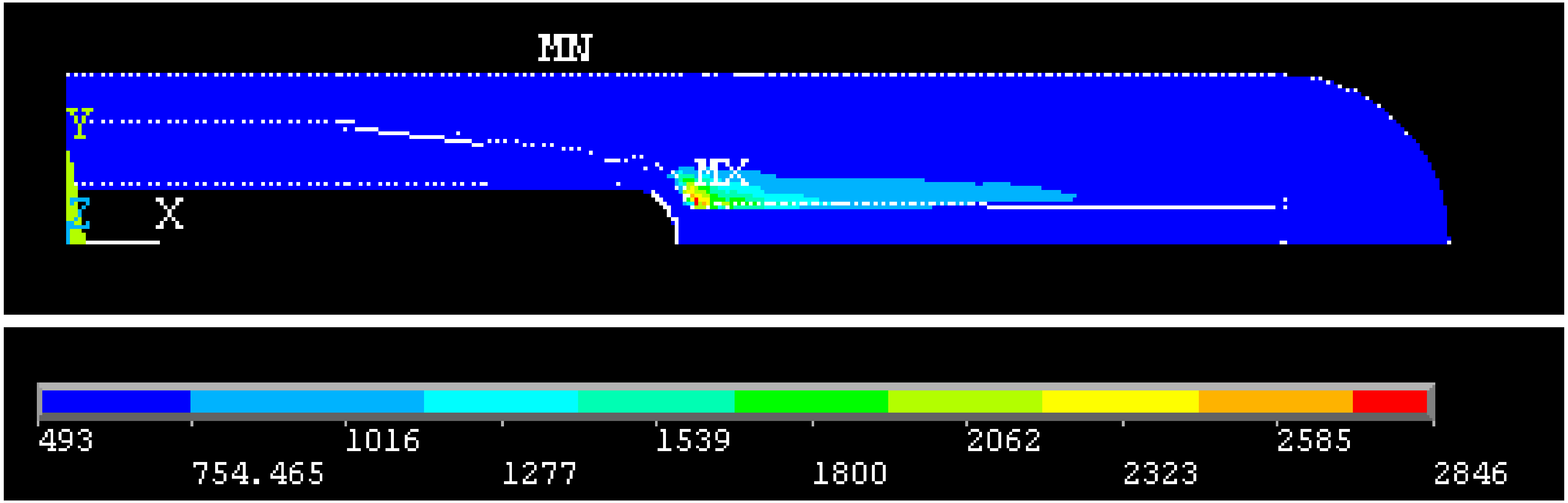
GEOMETRY-1
FLOW-GUIDE DIAMETER = 170mm

Grid Details

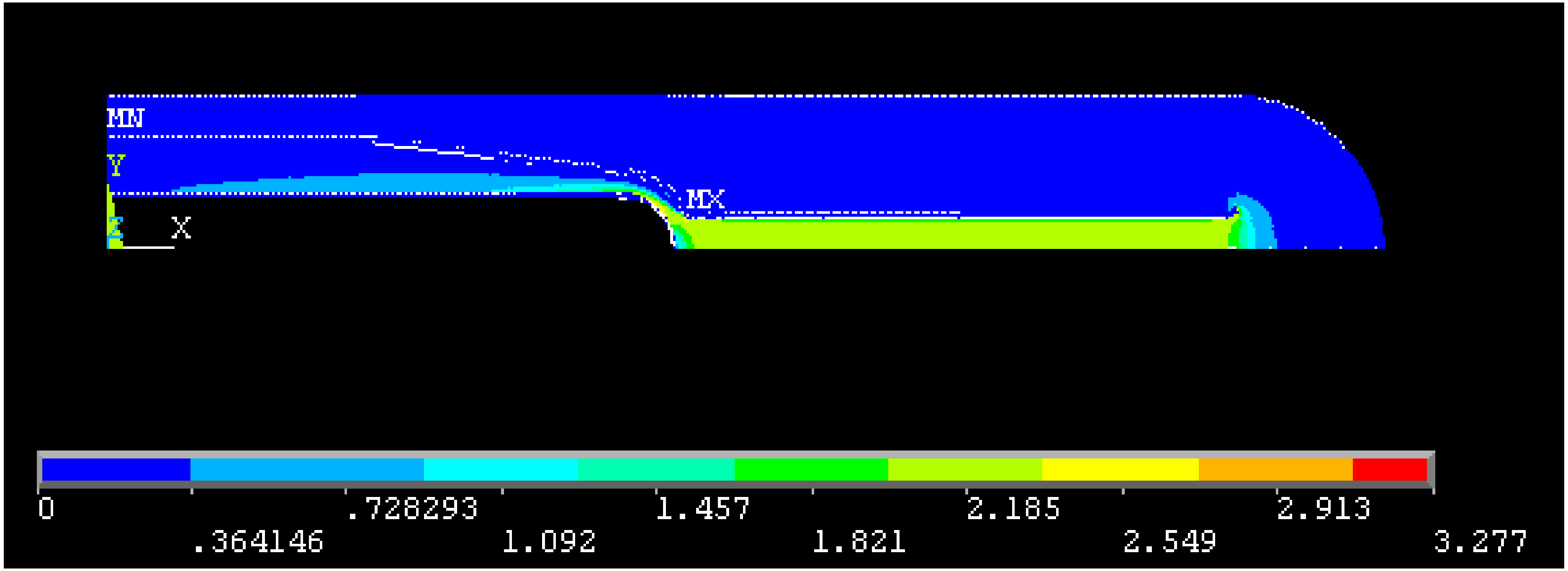


Total Number of Elements: 89,427

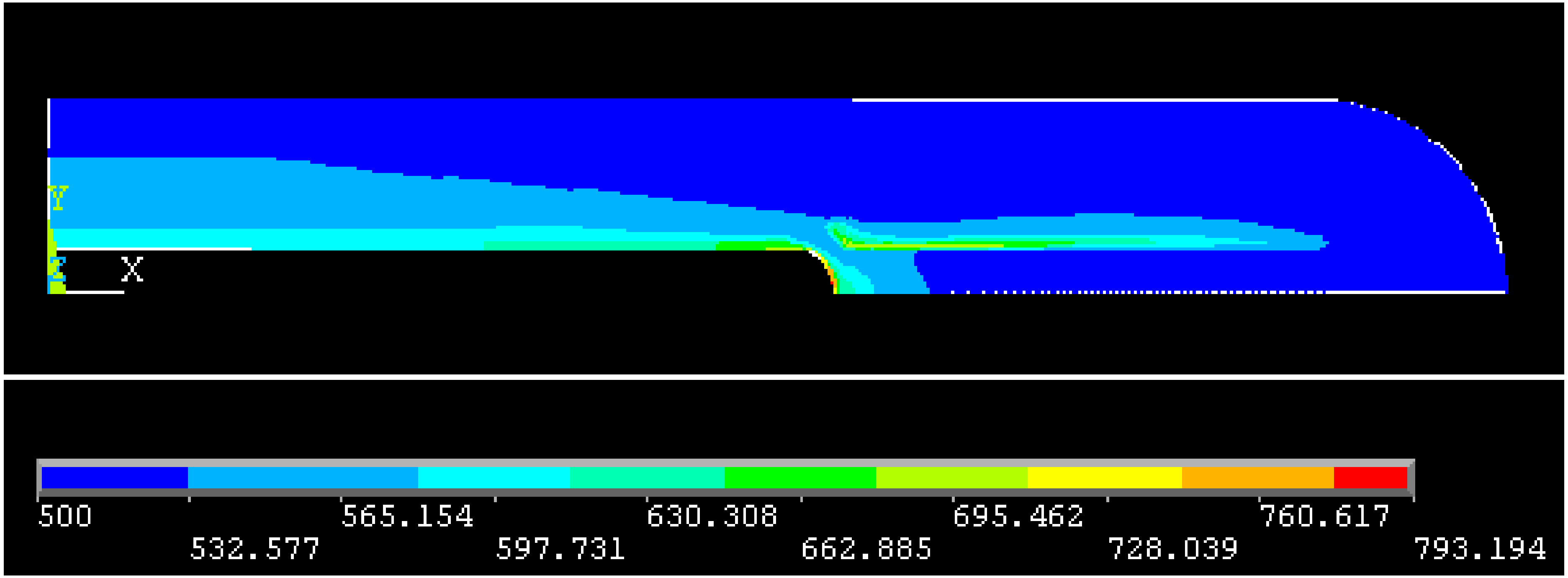
TEMPERATURE CONTOURS
FOR GEOM-1
FLOW RATE = 400 kg/s



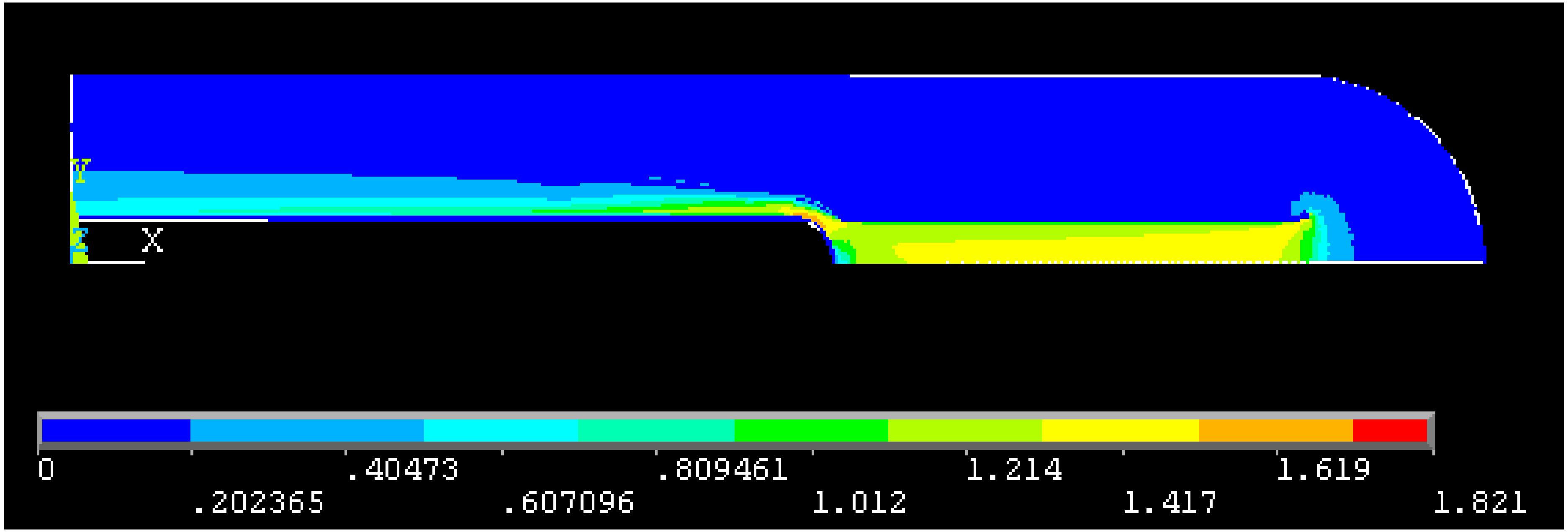
VELOCITY CONTOURS FOR GEOM-1
FLOW RATE = 400 kg/s



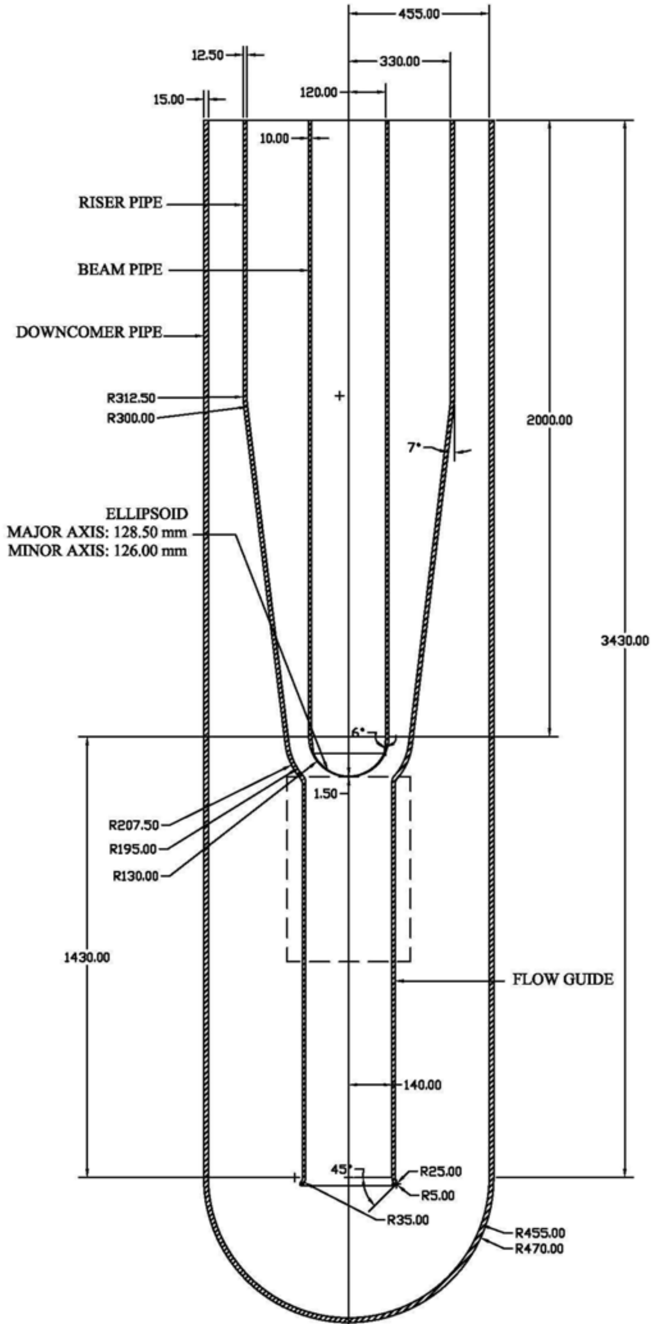
TEMPERATURE CONTOURS FOR GEOM-2 (FLOW GUIDE DIA = 240 mm) FLOW RATE = 550 kg/s



VELOCITY CONTOURS FOR
GEOM-2
FLOW RATE = 550 kg/s



Simulations in Final Optimized Geometry Using Different Turbulence Models



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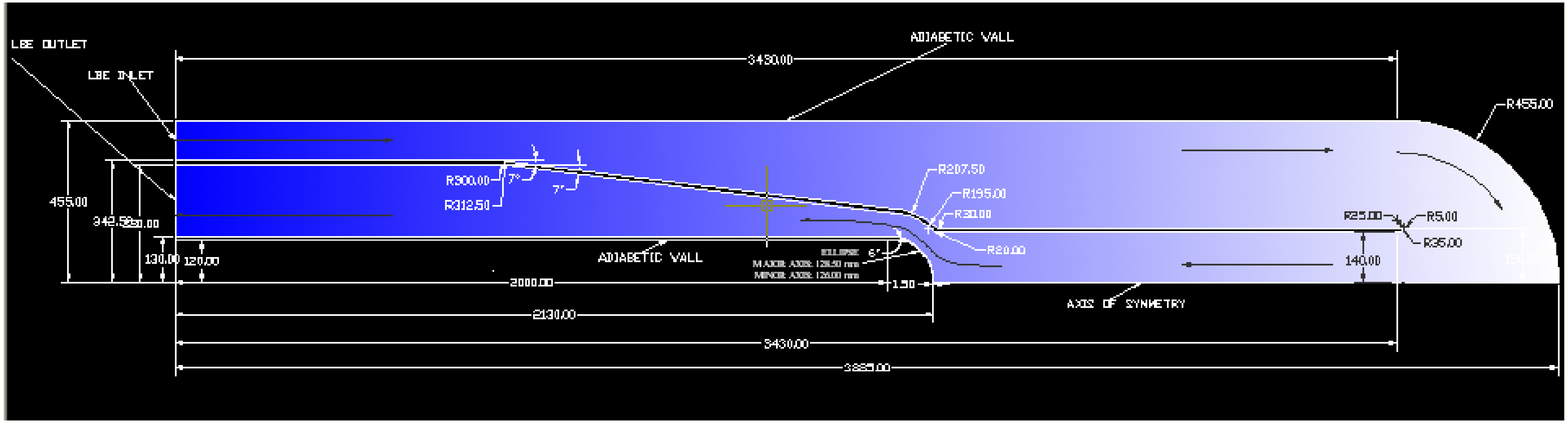
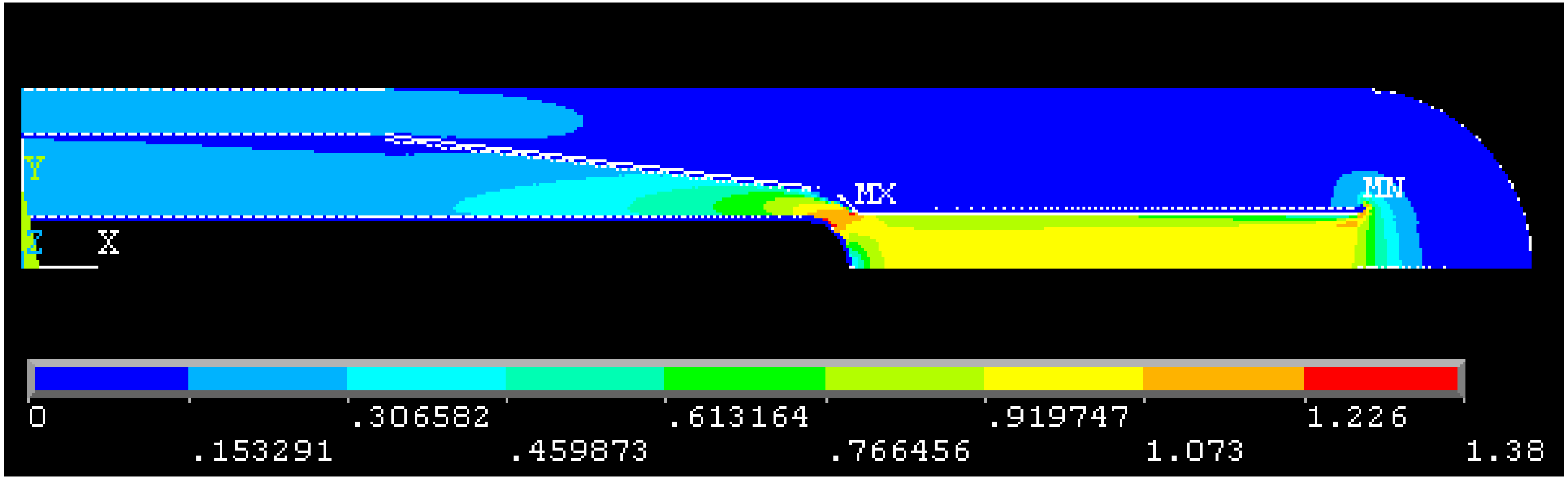
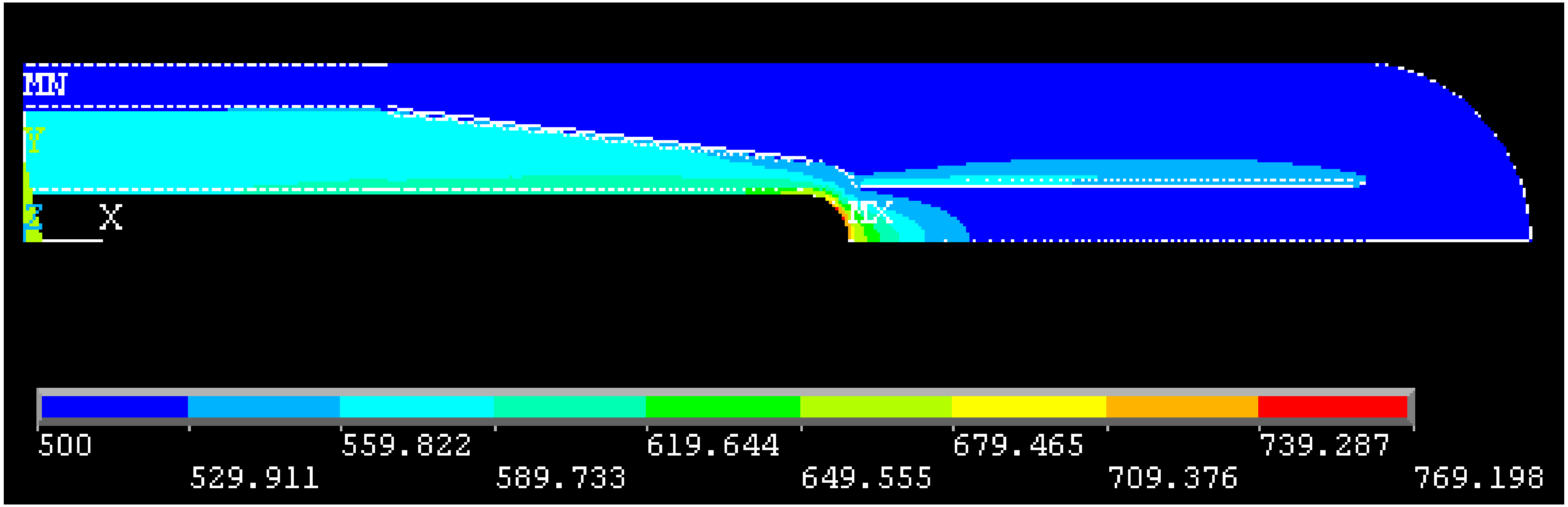


FLOW-GUIDE DIAMETER = 280mm

FLOW RATE = 600 kg/s

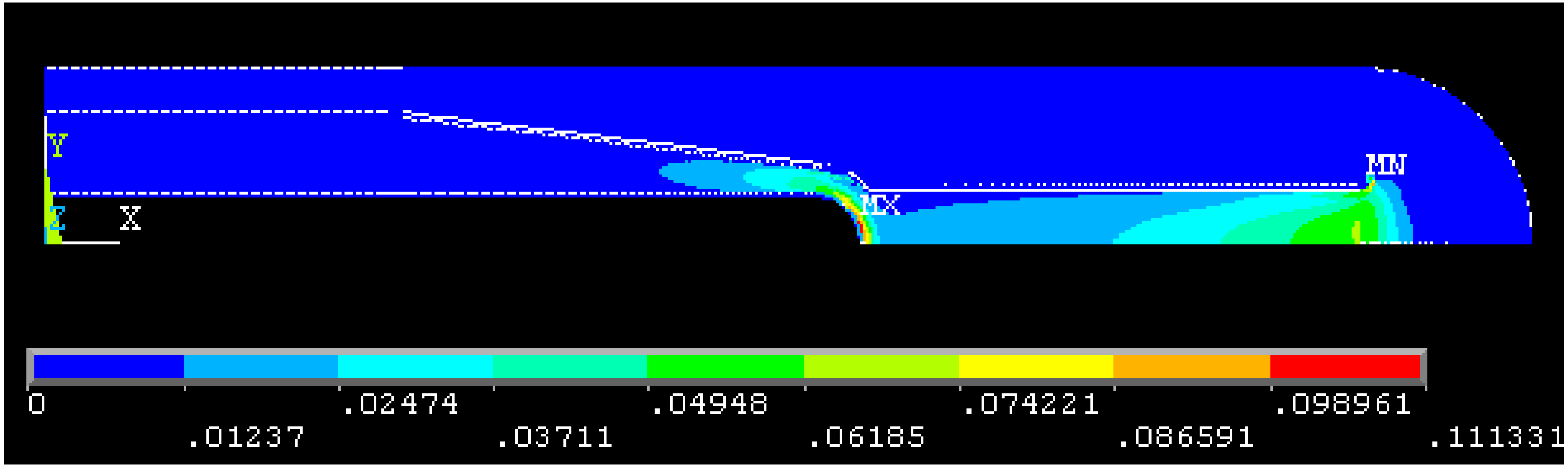


STANDARD k-ε MODEL
VELOCITY CONTOURS



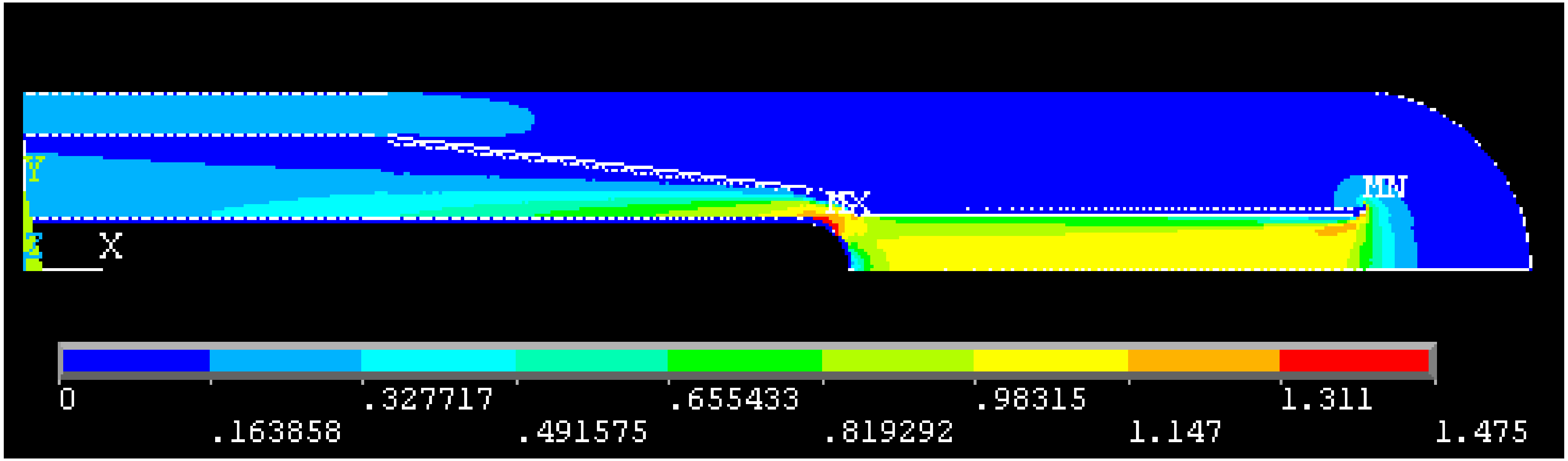
STANDARD k-ε MODEL

TEMPERATURE CONTOURS

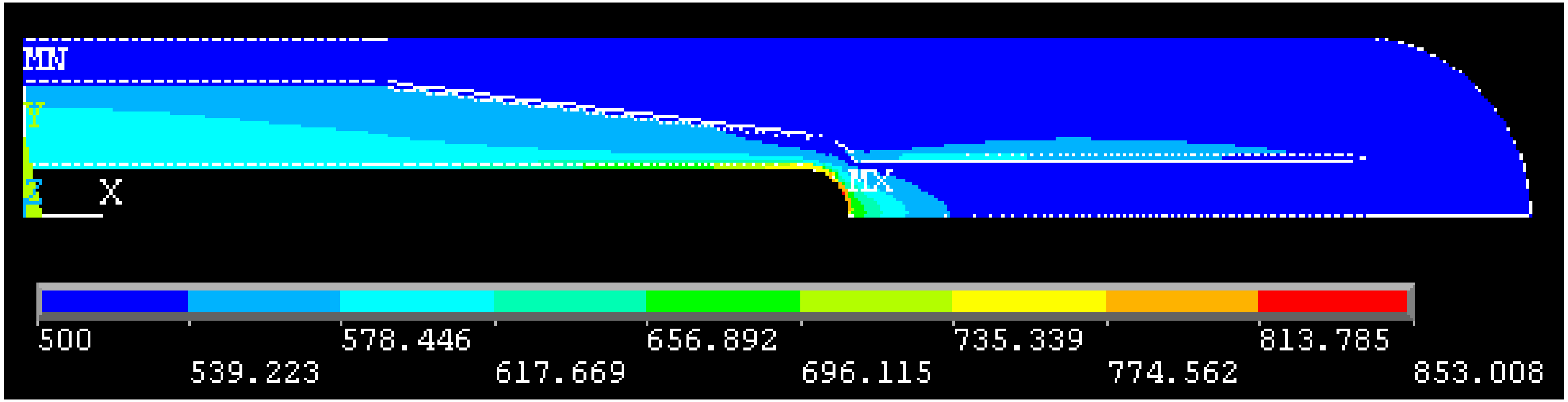


STANDARD k-ε MODEL

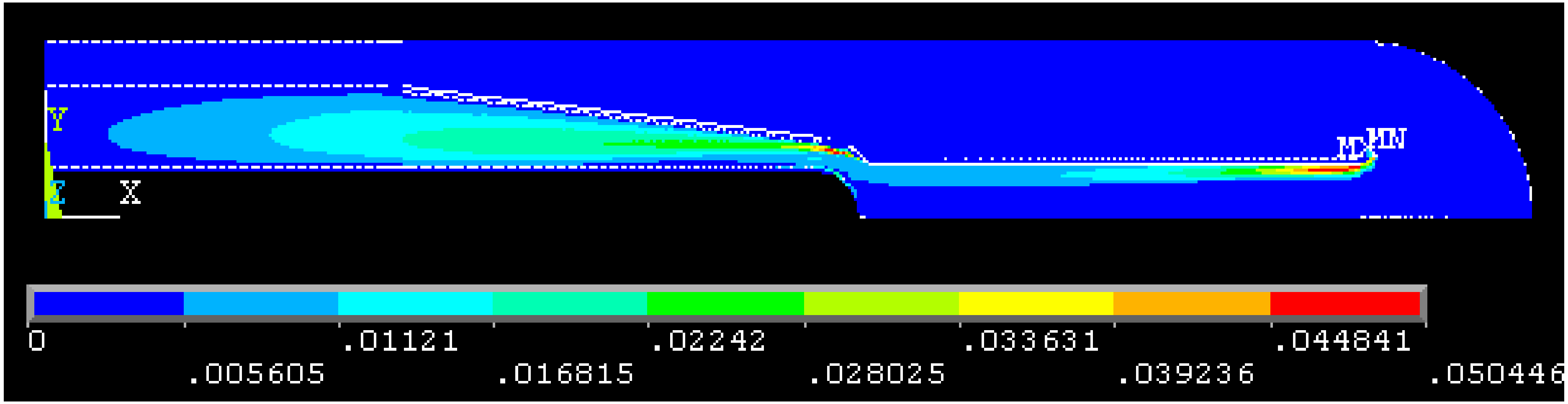
TURBULENT KINETIC ENERGY CONTOURS



k-ε RNG MODEL
VELOCITY CONTOURS



k-ε RNG MODEL
TEMPERATURE CONTOURS



k-ε RNG MODEL

TURBULENT KINETIC ENERGY CONTOURS

Results Summary with Different Turbulence Models

Model	Maximum LBE Temperature (K)	Maximum LBE Velocity (m/s)
Std k-ε	769	1.38
k-ε RNG	853	1.475
Std k-ω	759	1.354
k-ω-SST	760	1.347

Thank you for Attention