Food Processing with Air Impingement Systems – Heat Transfer in Cylindrical and Flat Shaped Objects

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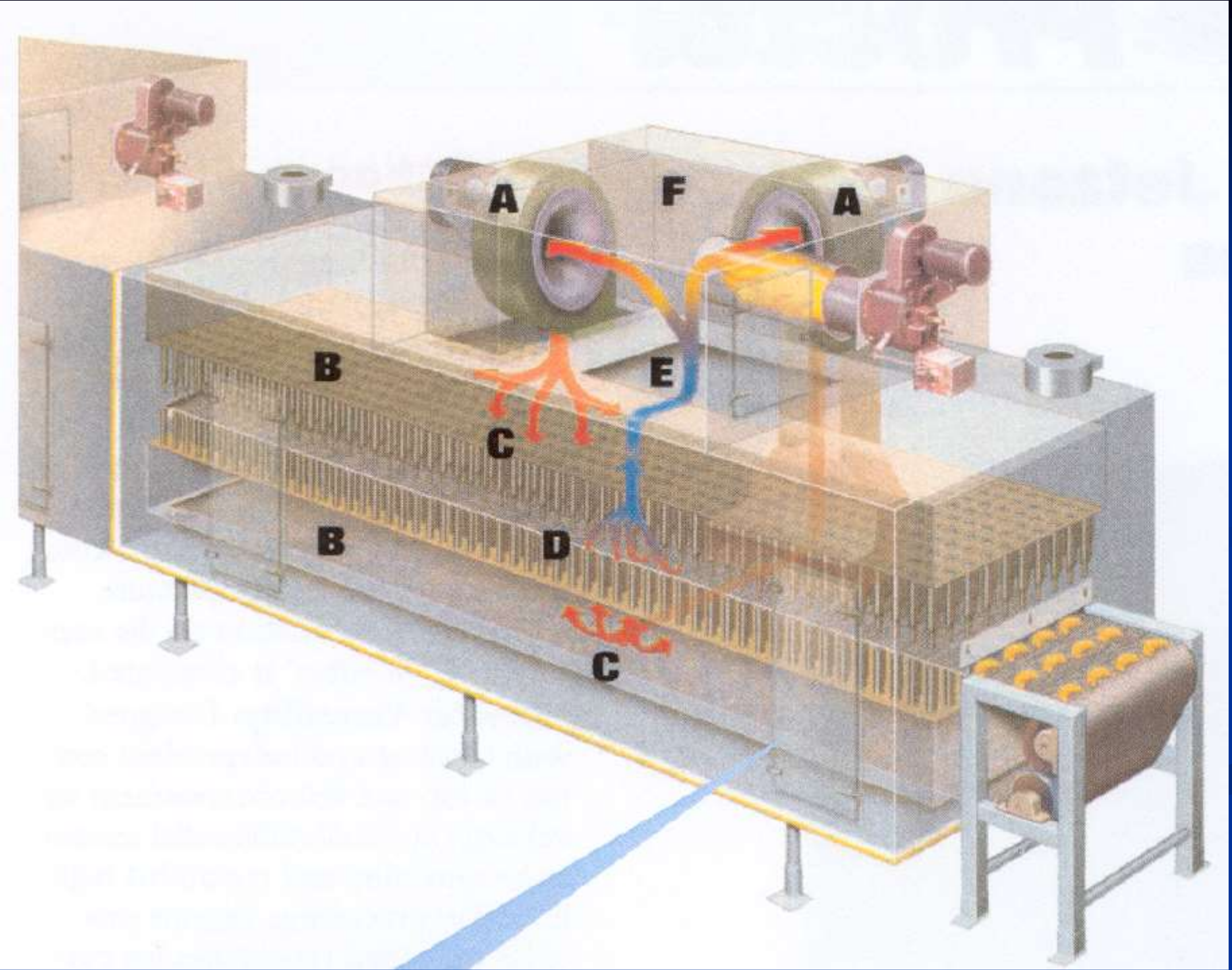
- Food industry is often seeking processes that result in low per-unit cost.
- Continuous processing is preferred over batch systems
- Processes that require shorter times are preferred.
- Low cost processing aids – water, air
- Air is used in numerous processes.

Significant reduction in cook times

Product	Time, min (Conventional oven)	Time, min (Microwave Impingement oven)	Reduction
Turkey	210	80	61%
Biscuits	12	2:30	79%
Brownies	28	6	79%
Corn dog	15	2:30	83%
Baked potatoes	60	9	85%
Turnovers	22	5	77%


A
F
A
B
E
C
B
D
C

Foodservice - Pizza Hut, Dominos, Red Lobster

An Impingement Oven

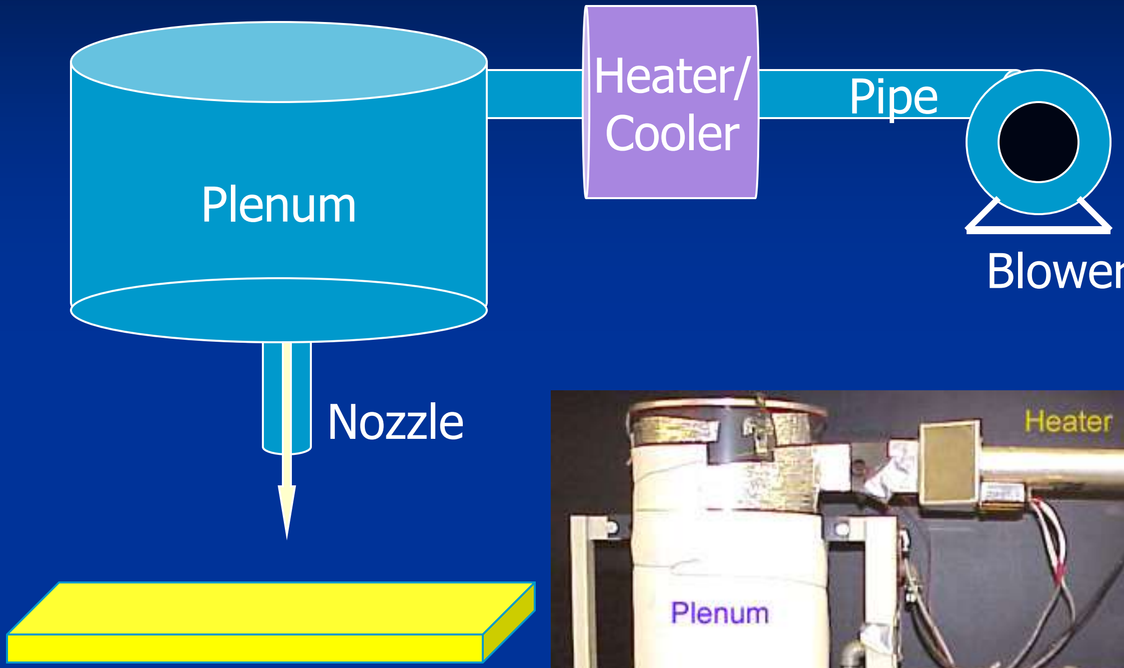
Overview

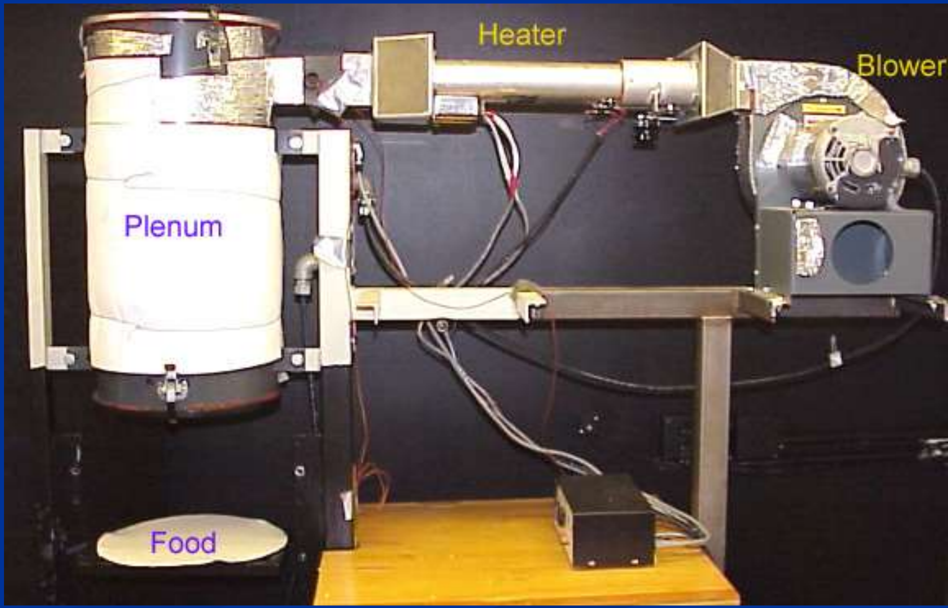
- Fluid flow in impingement systems
  - Design and operating variables
- Visualization studies
- Experimental trials
- Computational fluid dynamics and Particle Imaging Velocimetry
- Freezing, Thawing, and Cooling Studies

Rate of Heat Transfer

	h
	W/m^2 C
Natural Convection	6 to 11
Forced Convection to Flat Surfaces	13.6 @ 3 m/s 34 @ 17 m/s
Convection Ovens	22 to 45
Impingement Ovens	68 to 170

Air Impingement System

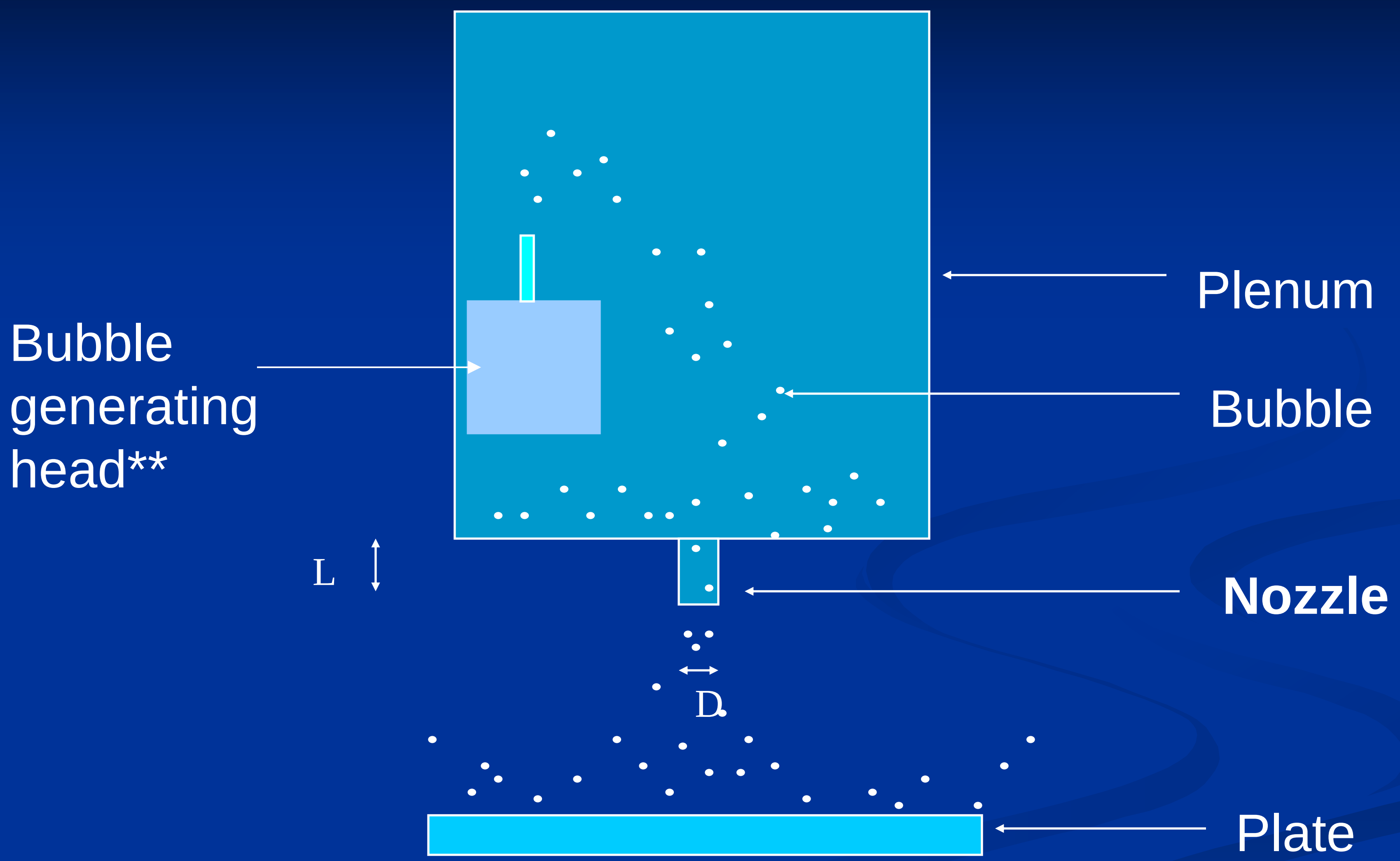




Published Literature

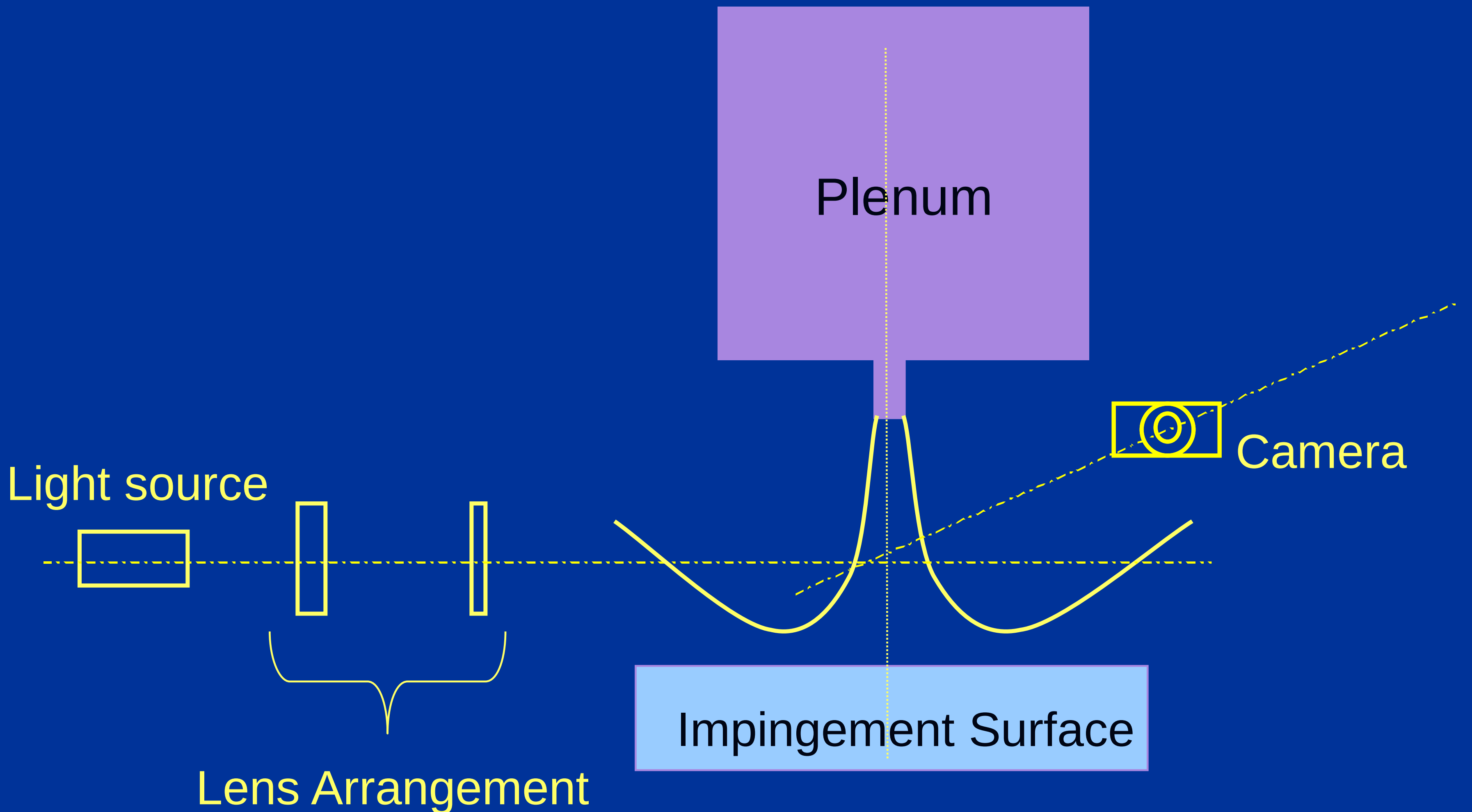
- Ford Motor Company 1960s Glass Division Technical Center, Gardon et al.
- Procter and Gamble Co., 1993, Polat et al.
- Institut fur Thermische Verfahrenstechnick der Universität Karlsruhe, Germany, 1977, Holger Martin
- Swedish Food Institute, SIK, Sweden,2000, Skjoldebrand
- Nottingham Polytechnic, UK, 1992, Jambunathan et al.
- Kansas State University, 1996, Walker et al.
- Rutgers University, 2001, Karwe et al.
- Texas A&M University, 2001, Moreira et al.
- Michigan State University, 2002, Marks et al.
- University of California, 2002, Singh et al.

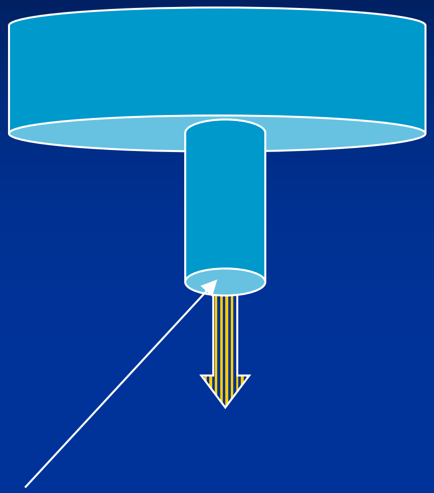
Tracer Particles (Helium Bubbles) in an Impingement System



**Bubble generating system (Sage Action Inc., Ithaca, NY)

Visualization of Fluid flow

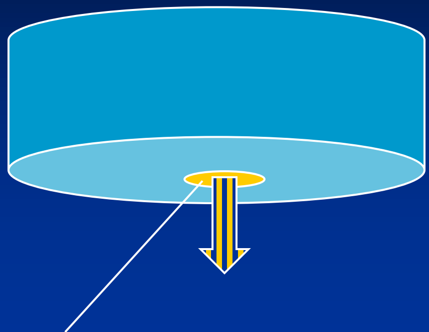




Diameter = 1.5 cm

Length = 7.5 cm

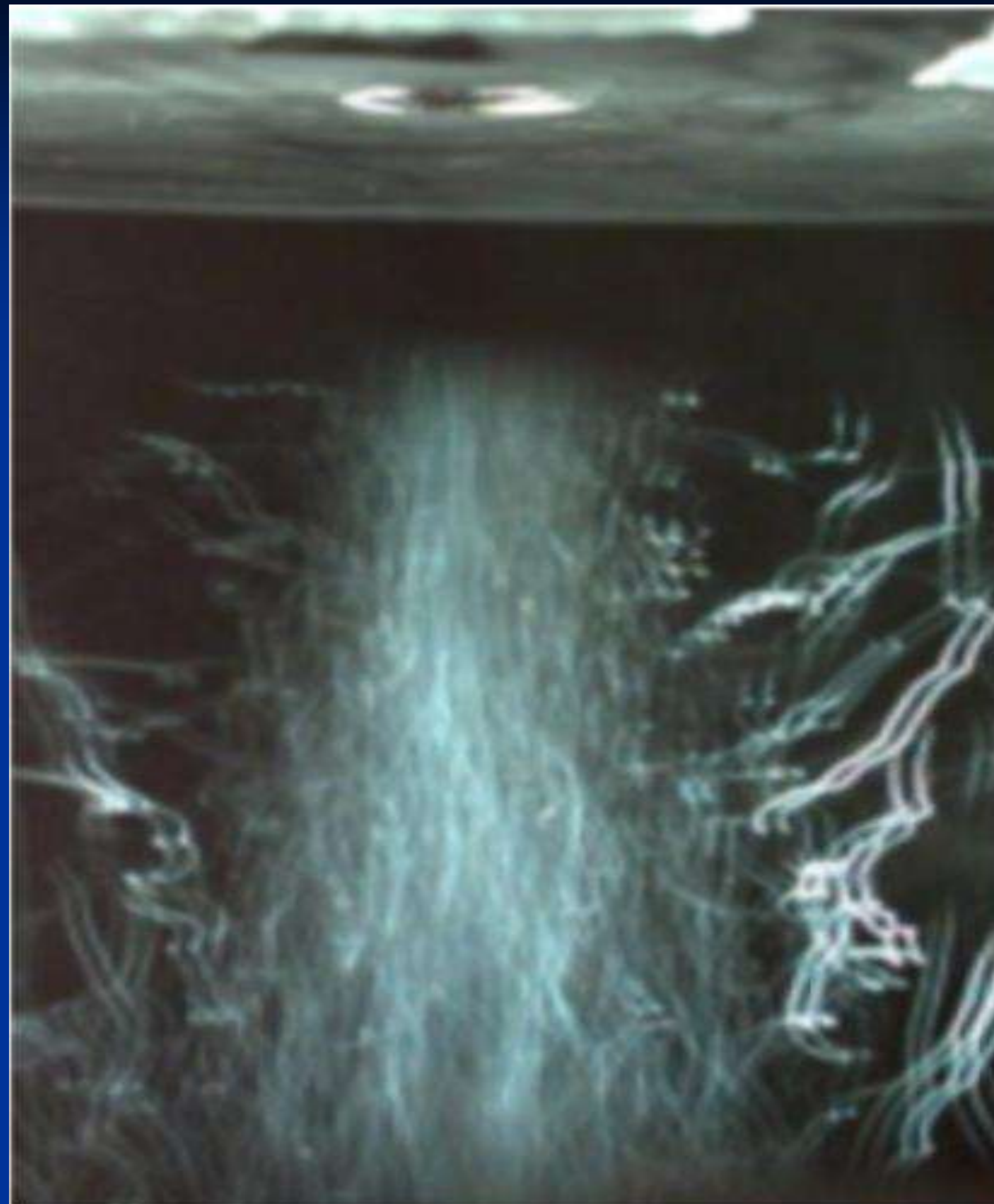
D/L ratio =0.2



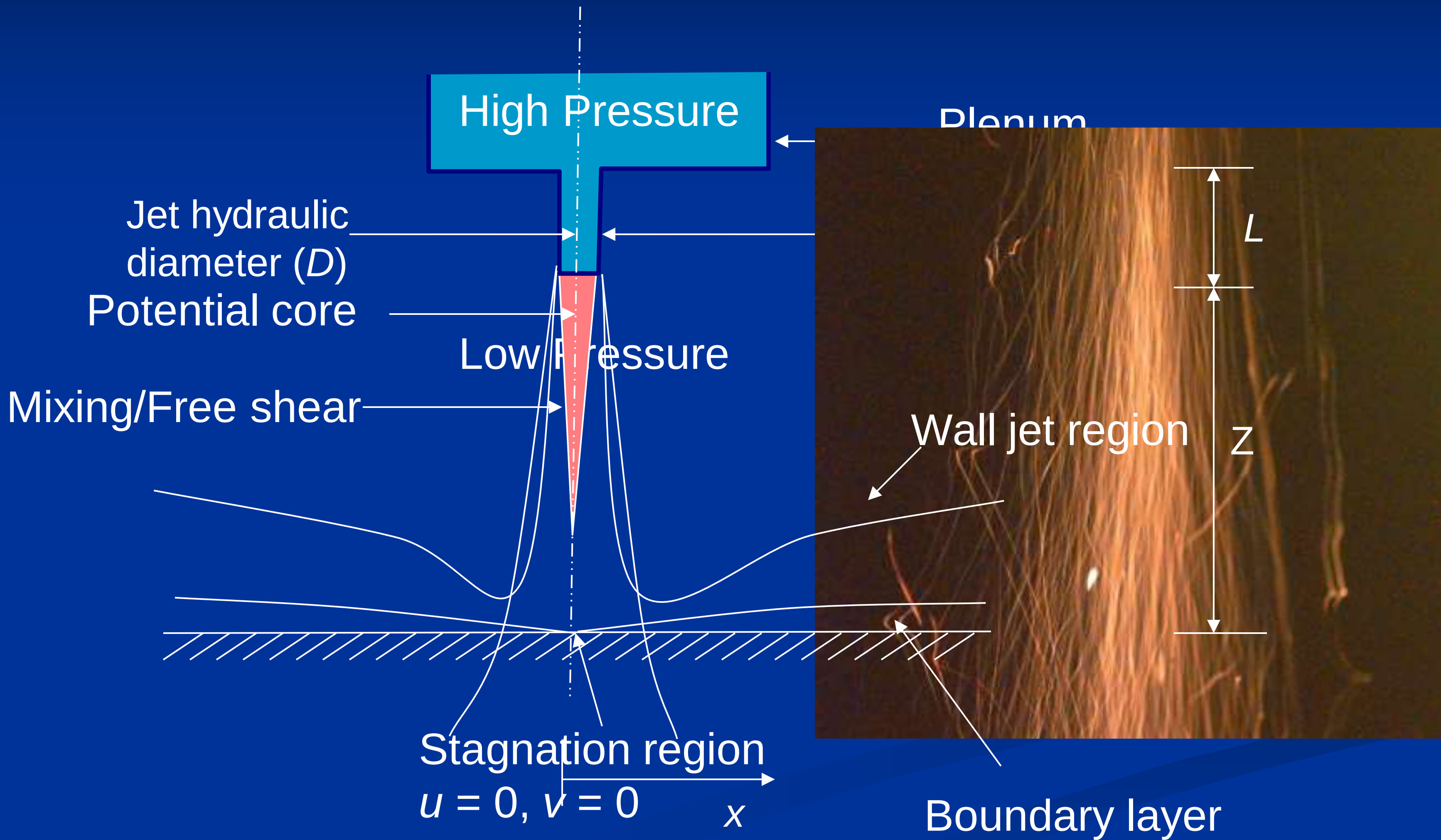
D = 1.5 cm

L = 0.79 cm

D/L ratio =1.9

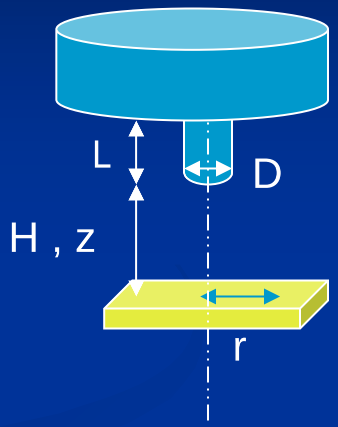


Principle of Impingement



Design Considerations

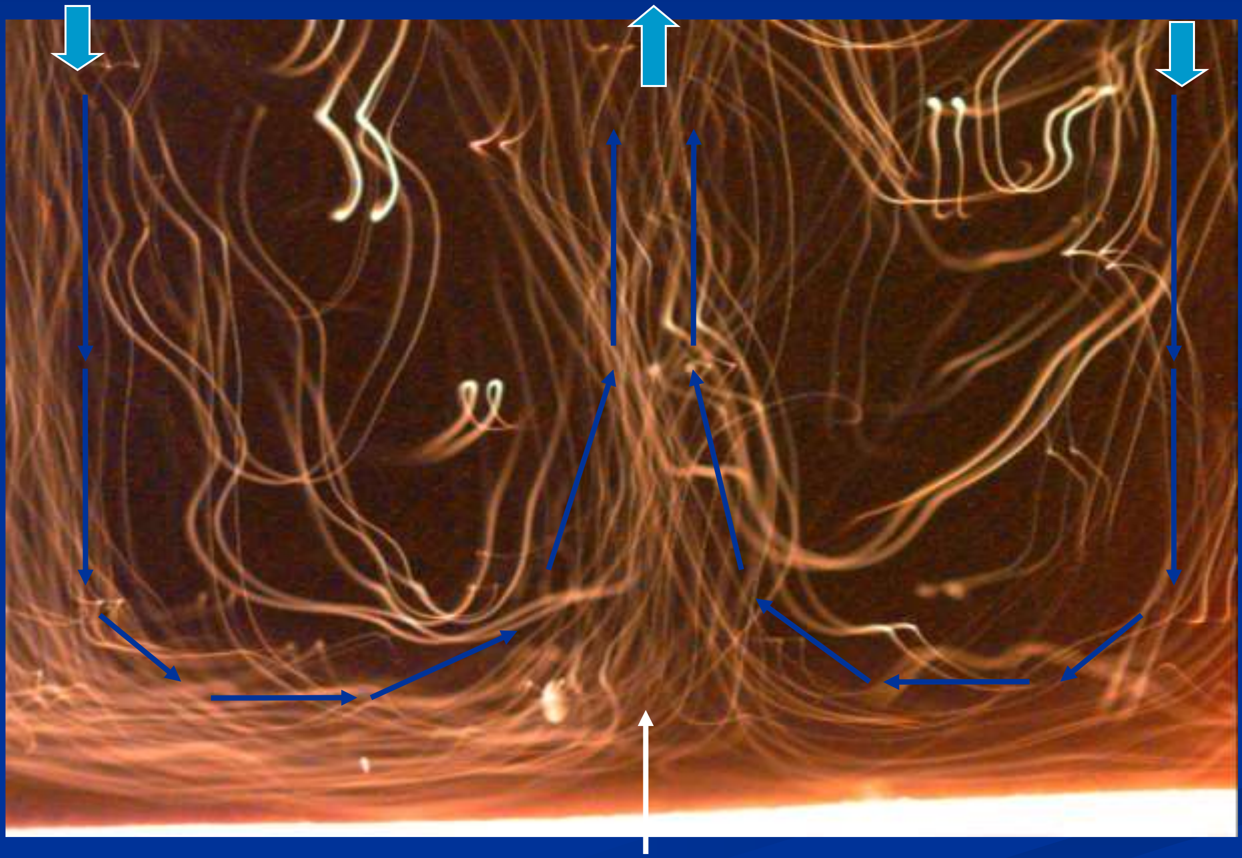
- Jet type (round of slot)
- Jet configuration (array geometry)
- Nozzle to target surface spacing
- Location of exhaust ports
- Induced or imposed cross flow
- Surface motion
- Angle of impingement
- Nozzle design
- Temperature differences between the jet and the impingement surface



Shape of the Impingement Nozzle

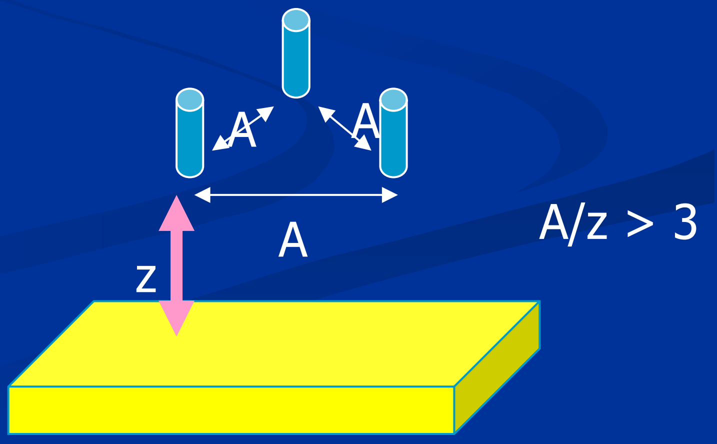
- Round nozzles
- Slotted (rectangular) nozzles
- Elliptical nozzles
- Within each shape, length of the nozzle to diameter is an important variable
- Sharp edged or tapered nozzle and length of nozzle affects degree of turbulence

Principle of Impingement : Multiple Jets



Number of Impingement Nozzles

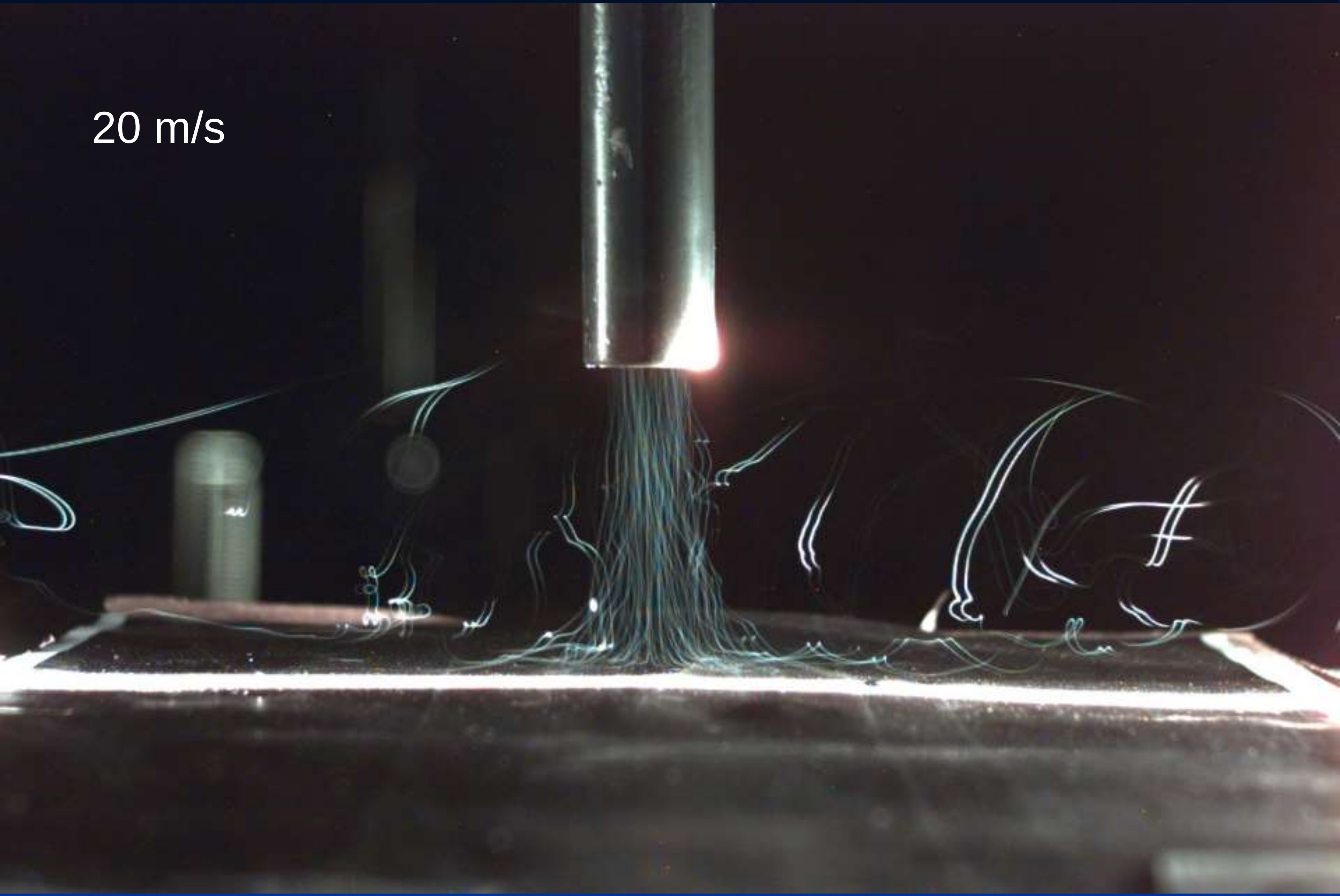
- Most studies carried out with single nozzles
- All industrial applications use array of nozzles where the air jets may interact with each other.



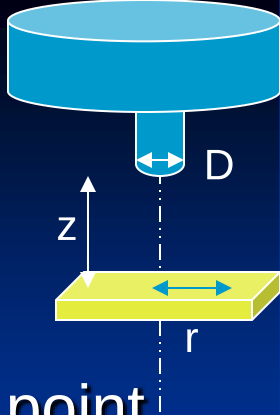
Air velocity

- Recall: Heat transfer coefficient is contained in the Nusselt number, and velocity is contained in Reynolds number
- Correlation between Nusselt number and Reynolds number
- $N_{Nu} \alpha N_{Re}^{n}$

Where n ranges from approximately 0.48 to 0.8


20 m/s

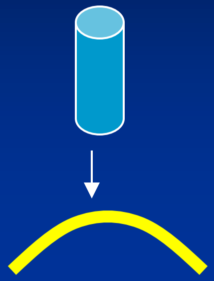
Distance from Nozzle to Impingement Surface



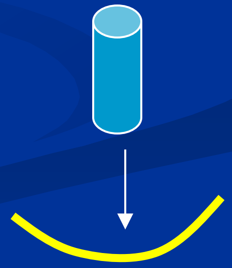
- Maximum Nusselt number occurs at the stagnation point when the jet is at a distance of six to eight diameters away from the impingement surface. This is the end of the potential core.
- A spatial variation in convective heat transfer coefficient occurs away from the stagnation point.
- When the distance from nozzle to impingement surface is small (z/D<6), there is a secondary maximum of Nusselt number at a radial distance of 0.5 to 2 nozzle diameters due to the transition from laminar to turbulent boundary layer flow

Geometrical shape of the Impingement surface

- Large number of studies with flat plates
- Convex and cylindrical surface



- Convex shape tends to thin the boundary layer at the impingement point causing an increase in heat transfer coefficient (Lee et al, 1997)
- Concave shapes: Nusselt number increases with increased surface curvature, the increase is due to turbulence (Choi et al, 2000)



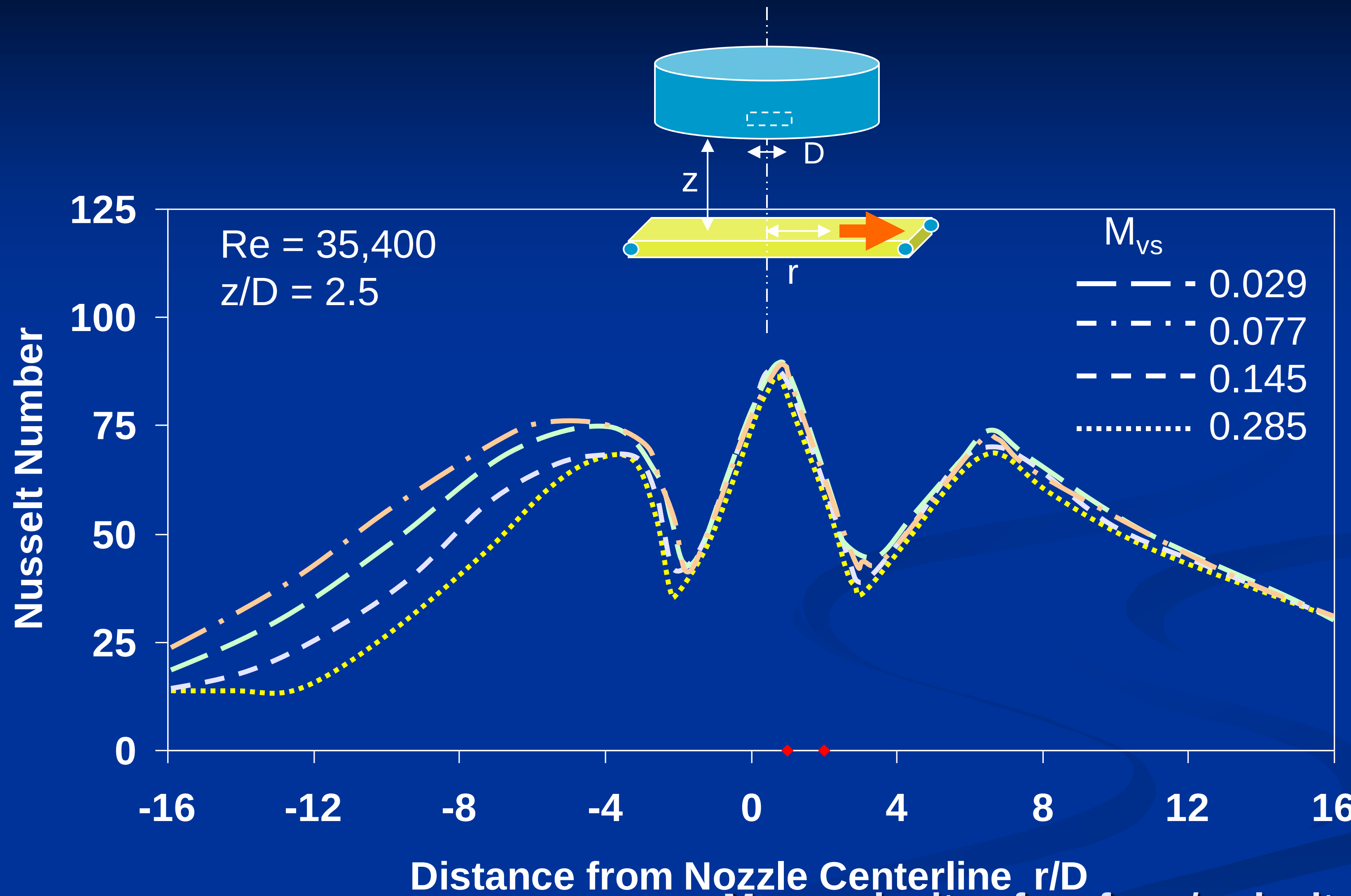
Impingement surface

- Roughness of the surface can also affect heat transfer rates. Nusselt number was about 6% higher for rough surface due to increase turbulence.

Surface movement

- Most experimental studies have been done with jets impinged onto a stationary surface.
- In industrial practice, the product moves under the jet while placed on a conveyor belt.
- Heat transfer was not affected when the velocity of the surface was less than 60% the velocity of the jet.

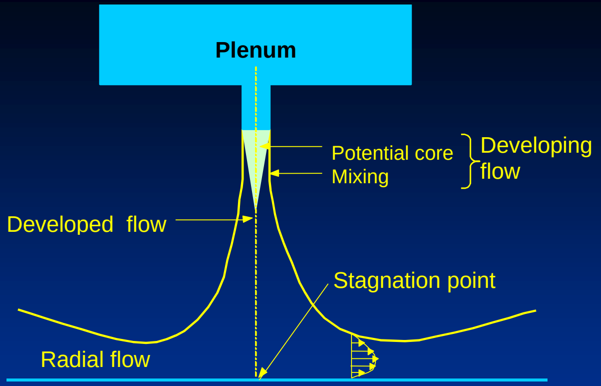
A single slot jet impinging on a moving surface



M_{vs} = velocity of surface / velocity of jet

Polat (1993)

Air Entrainment

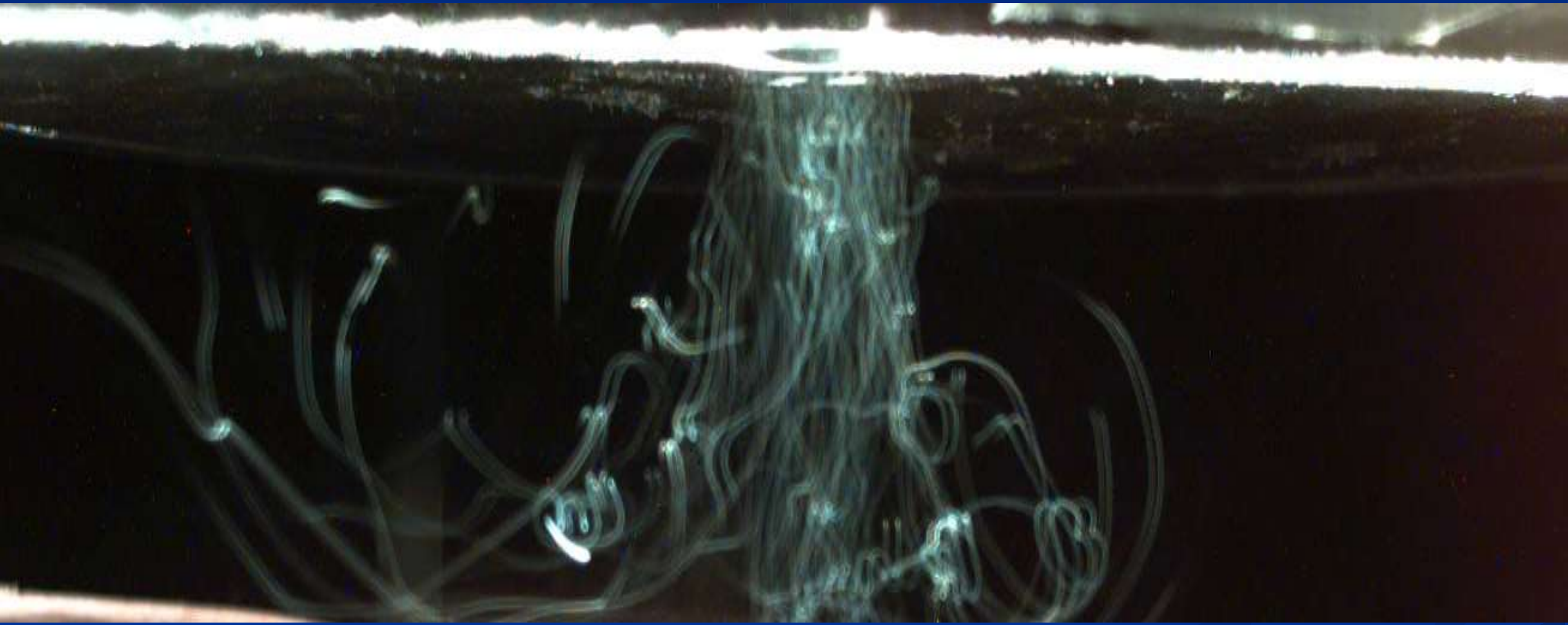


- Temperature of ambient air is different than that of the impingement jet
- Impingement heat transfer is affected by
  - Temperature of the air in the jet
  - Temperature of ambient air
  - Temperature of the surface
- When ambient air is cooler than the impingement jet, the ambient air becomes entrained in the jet flow and lowers the temperature of the flow reducing heat transfer (and vice versa).

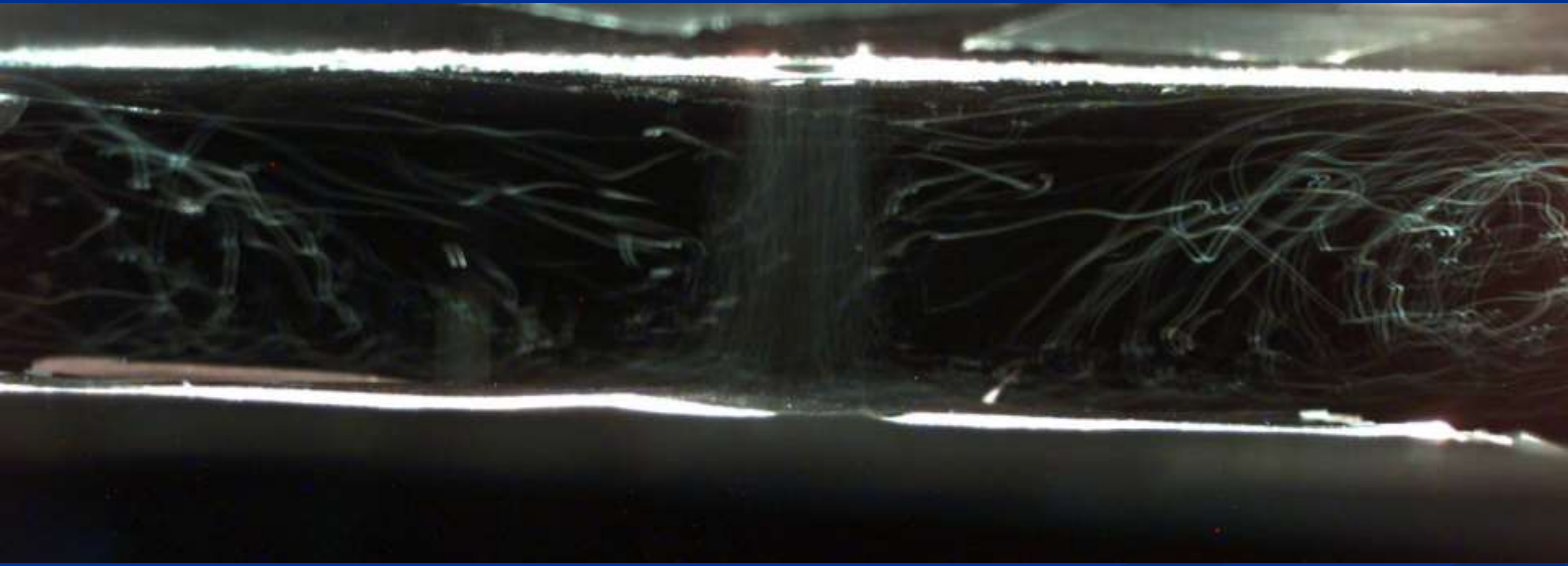
Confinement

- In industrial applications, the impingement nozzles are enclosed or shrouded in the equipment
- Enclosing the system, the ambient air temperature becomes nearer to the jet air, reducing the effect of entrainment.
- Exhaust ports may be placed between the nozzles. If located on the sides, flow field of jets may be drastically altered. Air exiting from center jets may influence jets on the sides.
- 15 – 30% decrease in N_{Nu} with cross-flow arrangement.

13.1cm

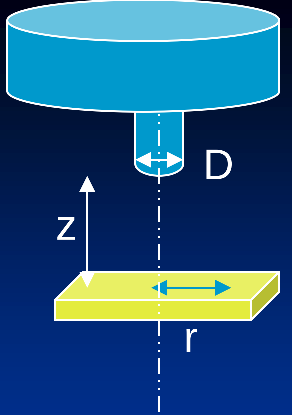


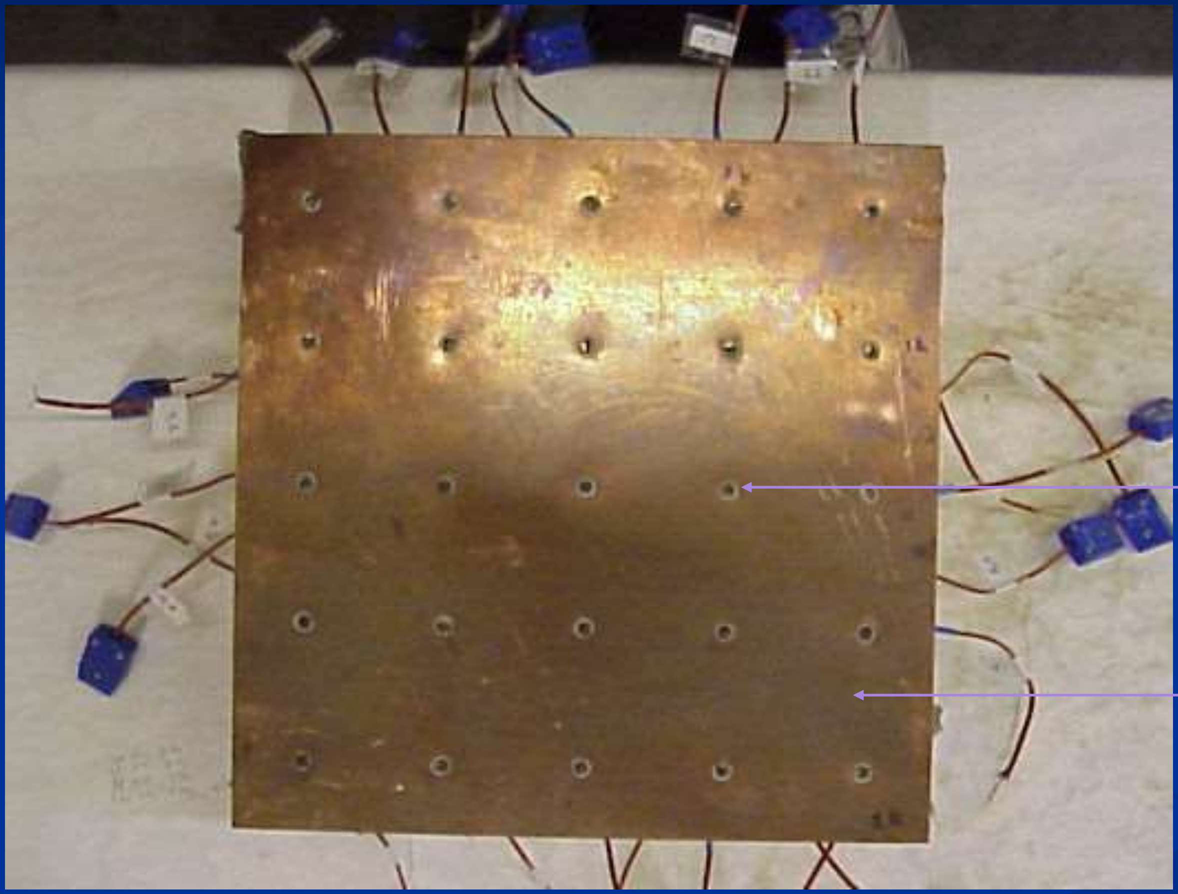
5cm



Jet-to-Jet Interaction

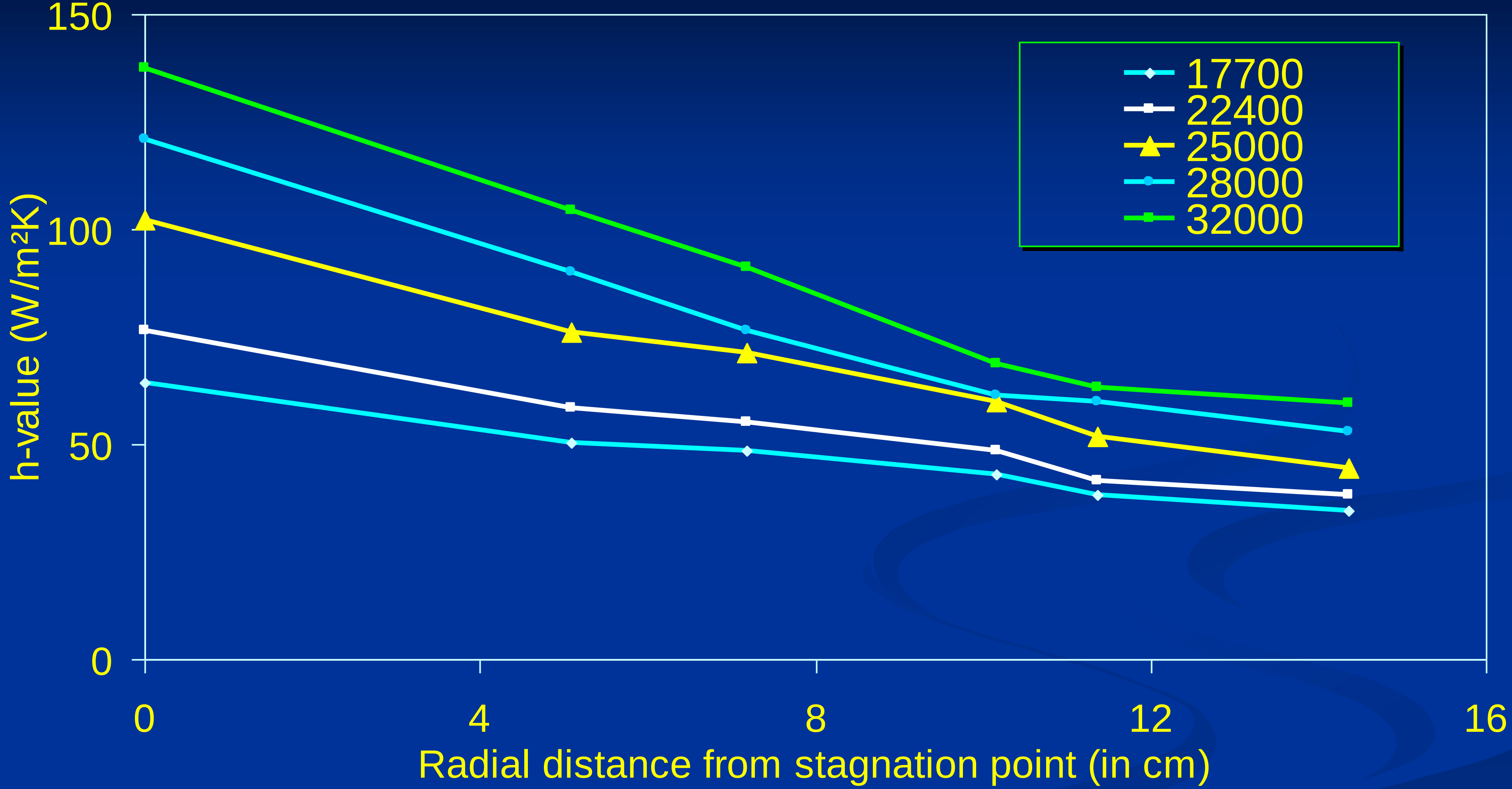
The Measurement Device



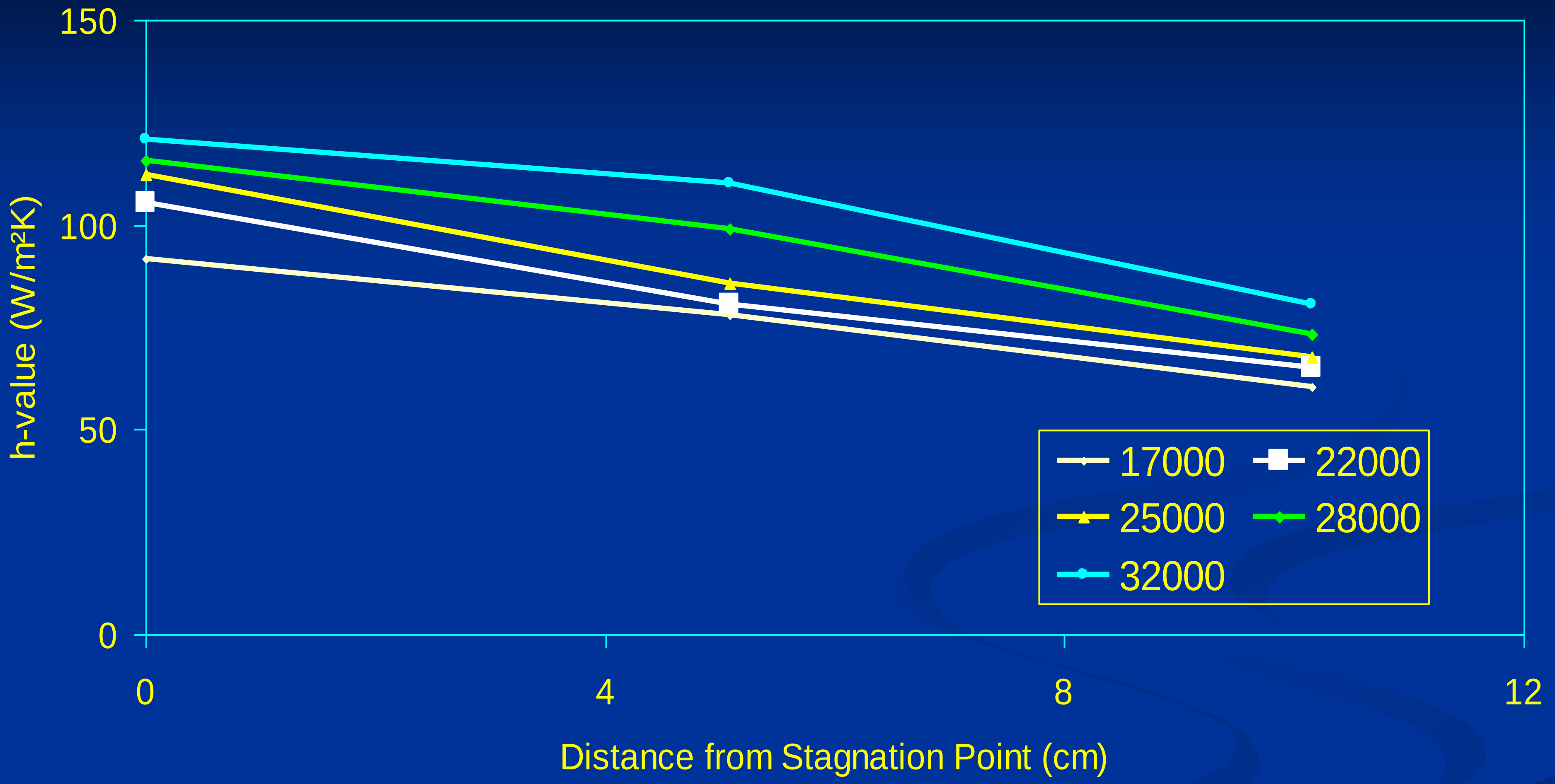


Top view

Convective Heat Transfer Measurement Setup



Heat transfer variations under single circular jets (76mm nozzle to plate spacing)

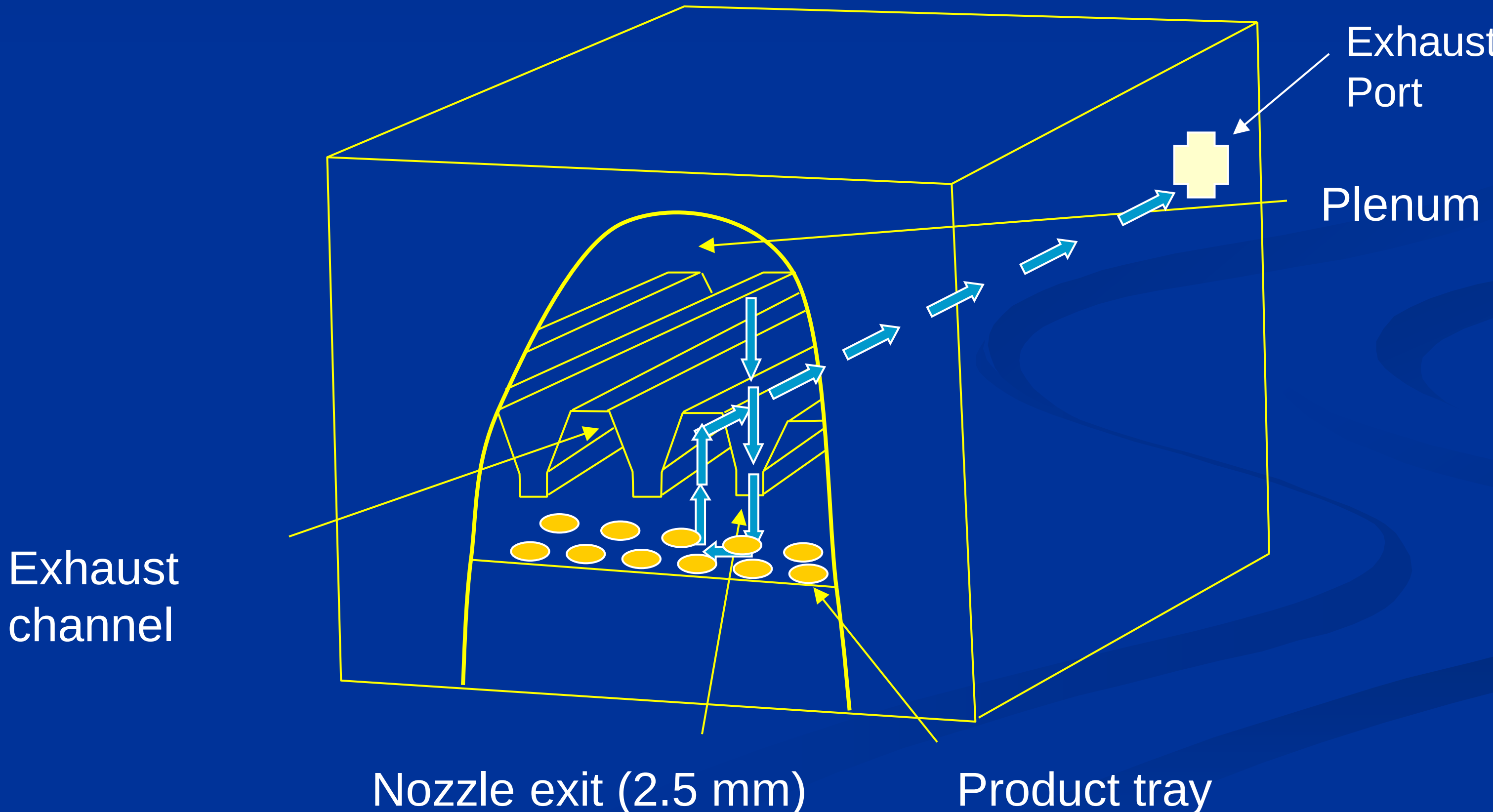


Heat transfer variations under single slot jets (76mm nozzle to plate spacing)

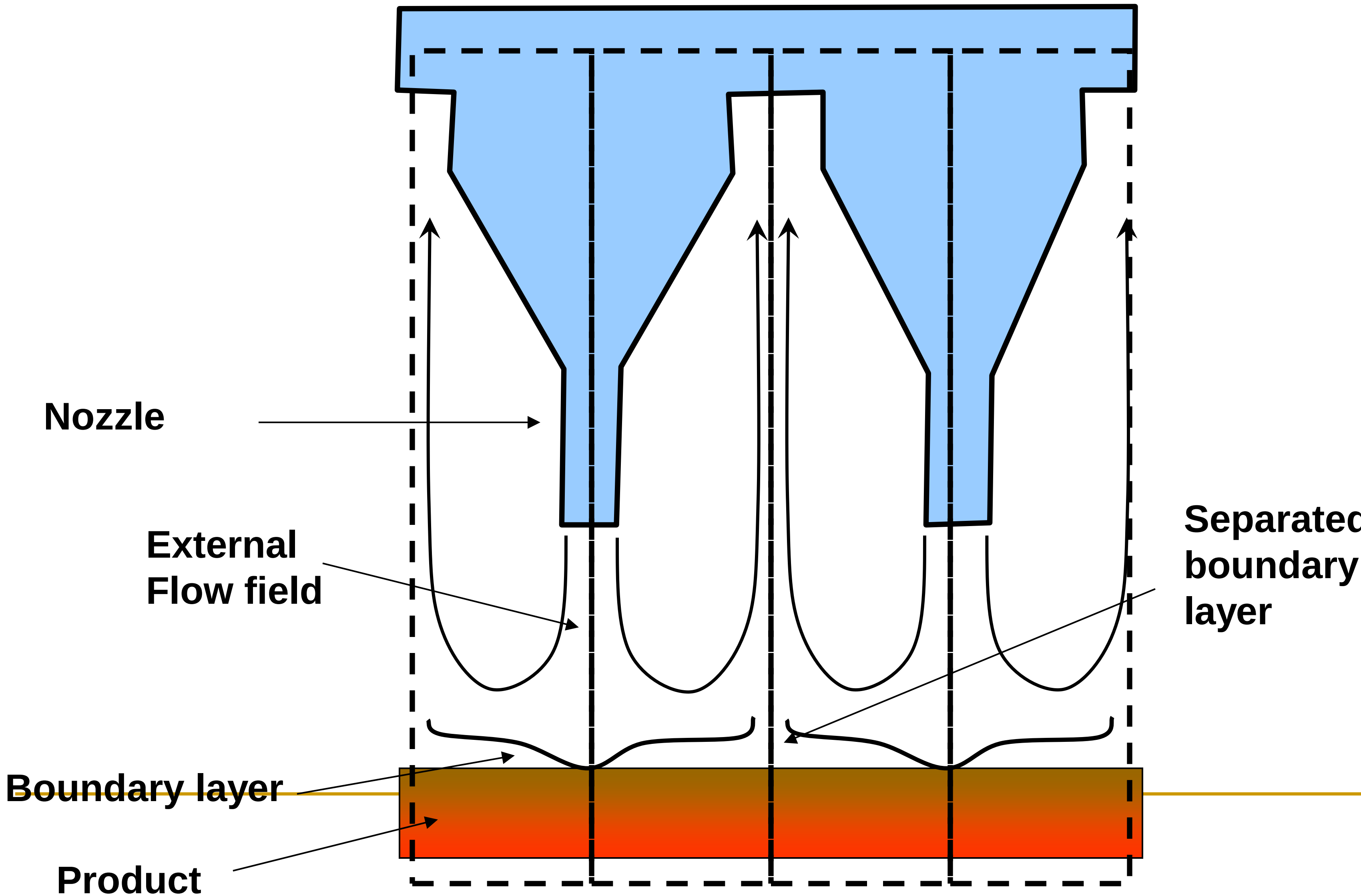
NEXT

Prototype Development

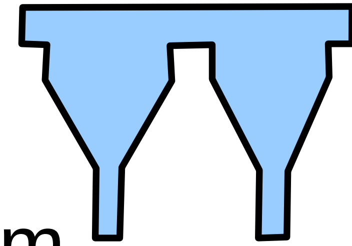
- Based on preliminary measurements, input from manufacturers and literature review



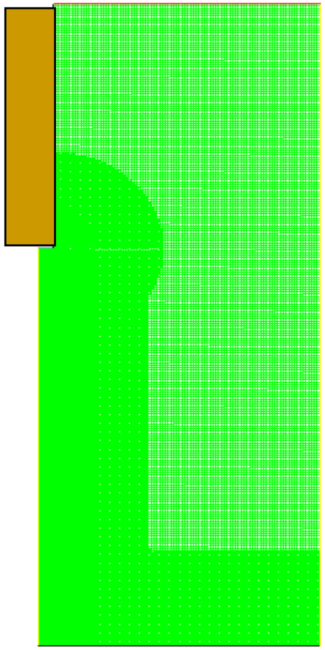
Development of Numerical Model



Numerical Model : External Flow

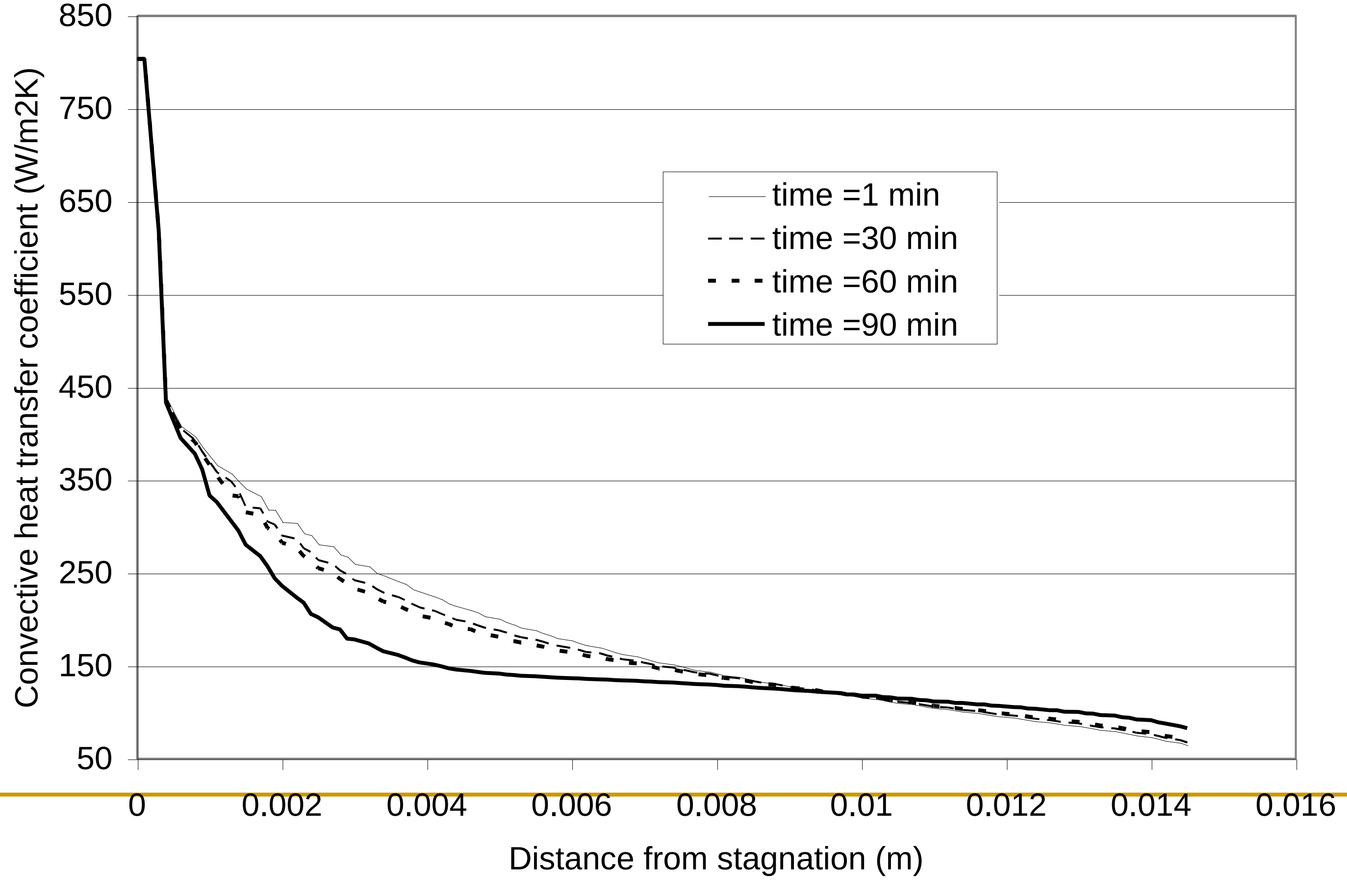


- External flow - steady, turbulent, problem
- Grid generation - GAMBIT 3.1 adaptive meshing
- Solution - FLUENT 6.0 comr solver
- Solver parameters
  - Implicit “SIMPLEC” scheme wi discretization
  - k-ε model for turbulence estimation

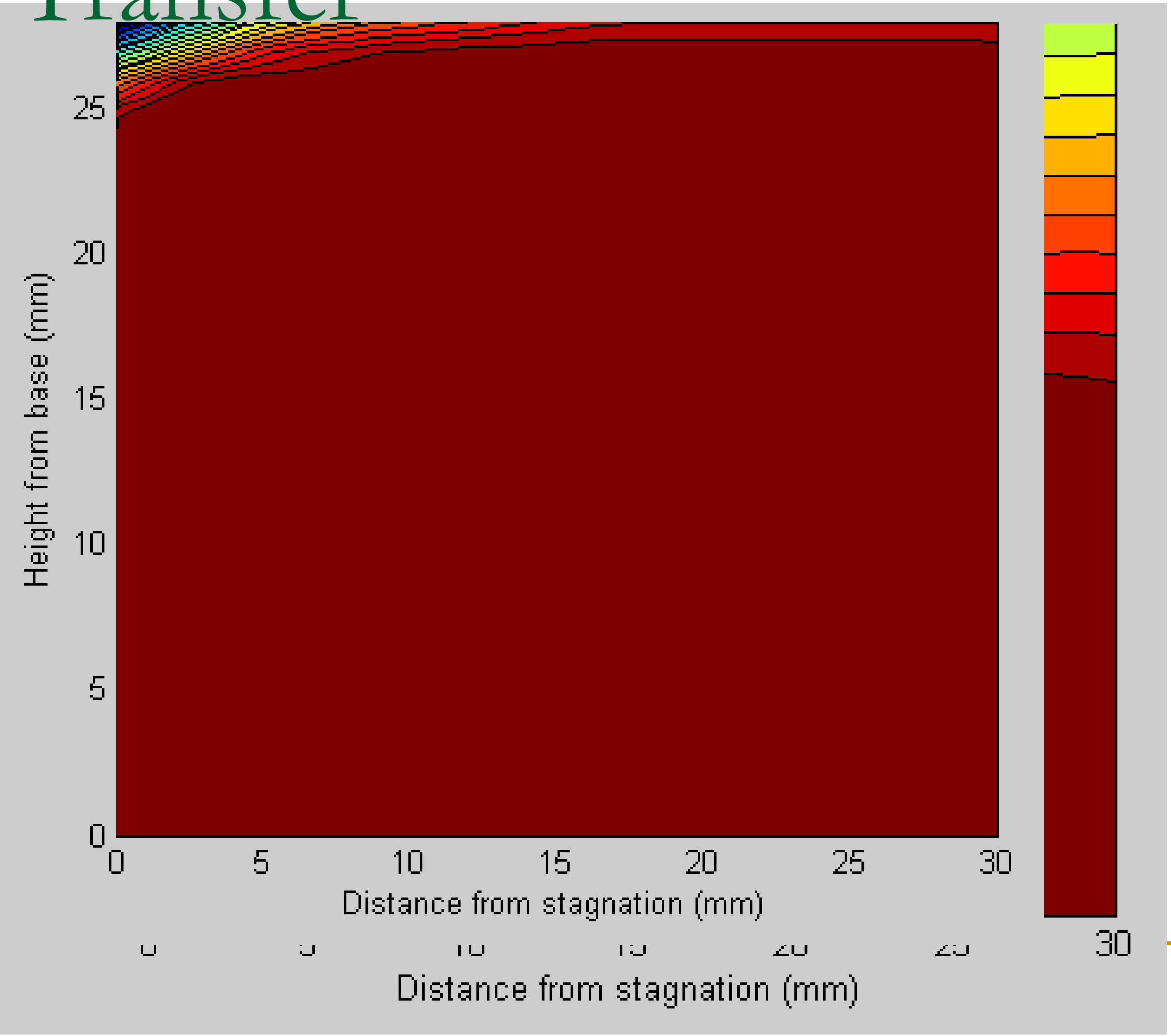


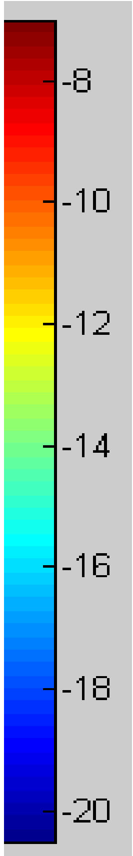
Heat Transfer Coefficient

- Heat transfer coefficients show considerable spatial and time dependence



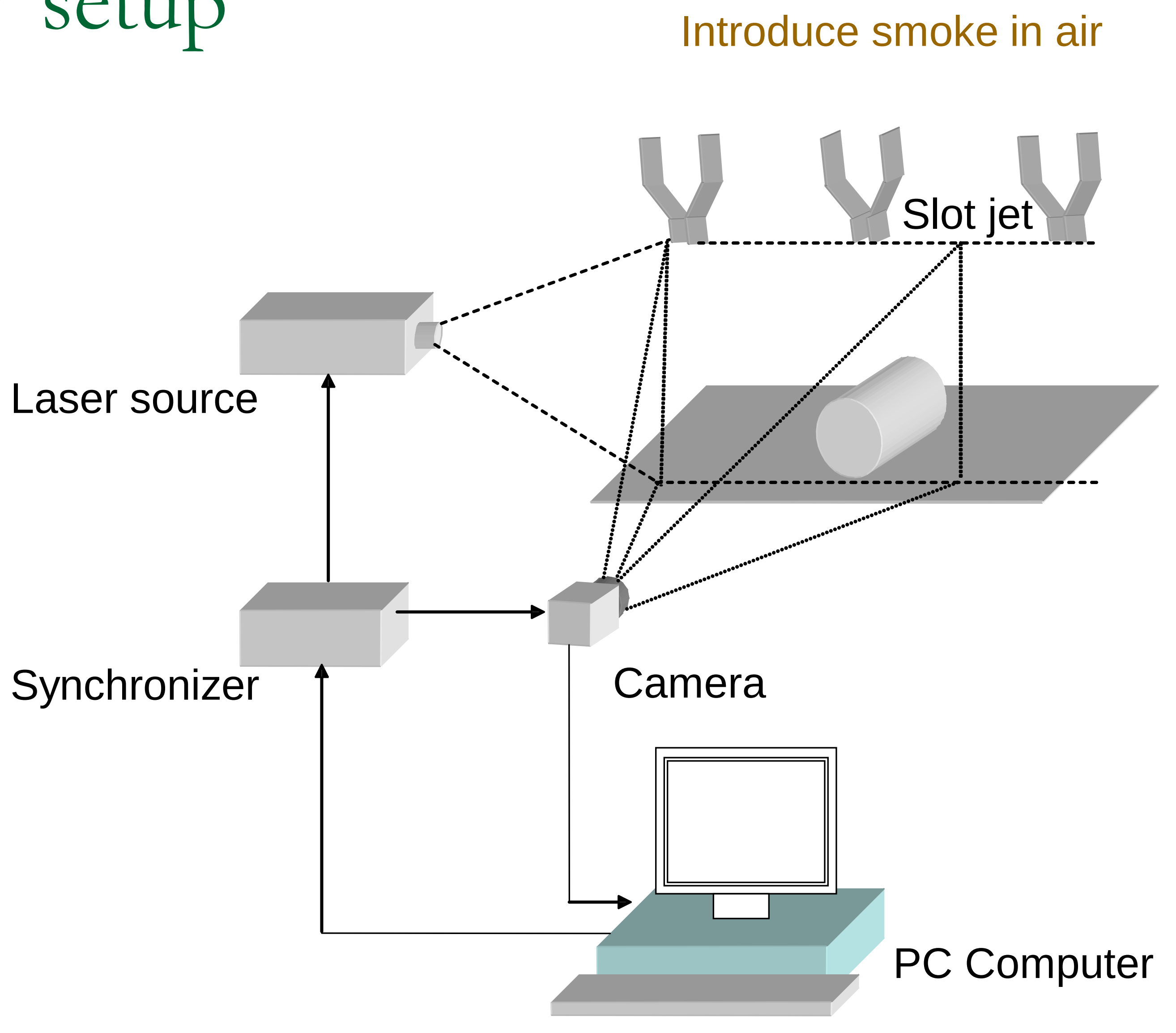
Simulation Results : Internal Heat Transfer





Temperature in °C

PIV setup



Introduce smoke in air
Slot jet
Laser source
Synchronizer
Camera
PC Computer

Cross-correlation to estimate velocity

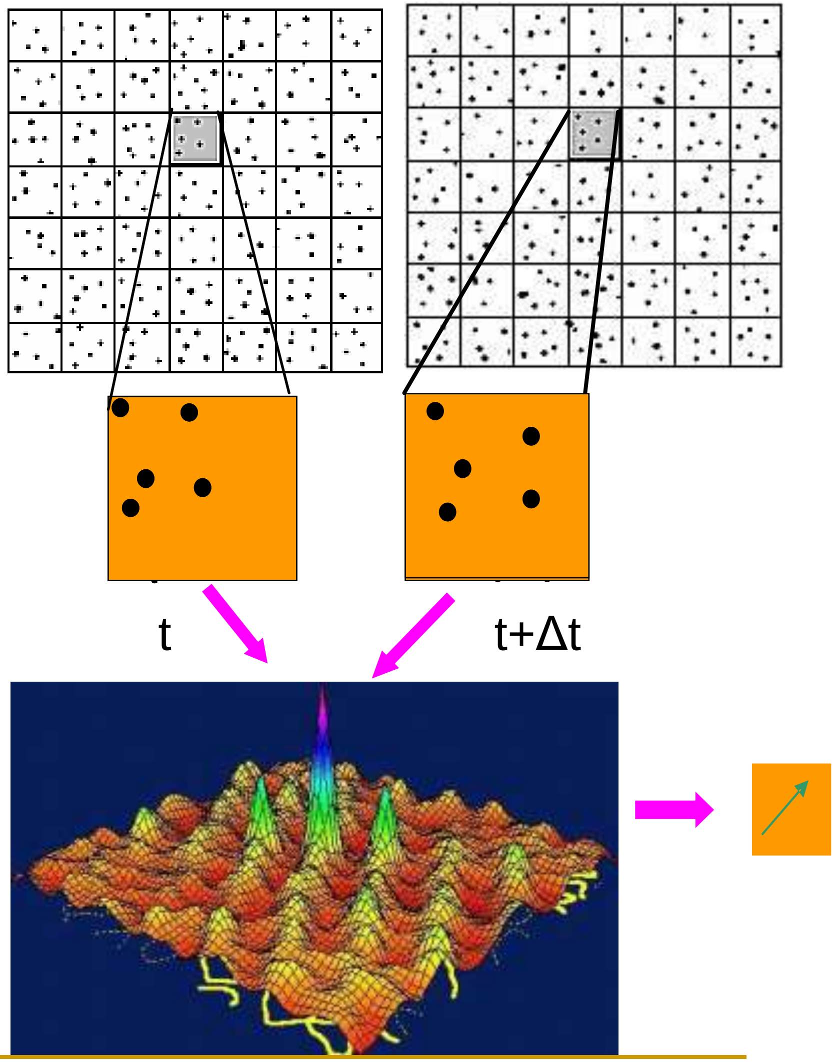
Pair of images are processed at once

Both images are divided in to smaller units of equal size called Interrogation-Areas (IA).

Corresponding interrogation areas from the two images are cross-correlated to estimate the displacement of particle Δx and Δy.

Knowing the time delay between two images, velocity in the particular region is estimated as

$$u = \frac{\Delta x}{\Delta t} \, and \qquad v = \frac{\Delta y}{\Delta t}$$



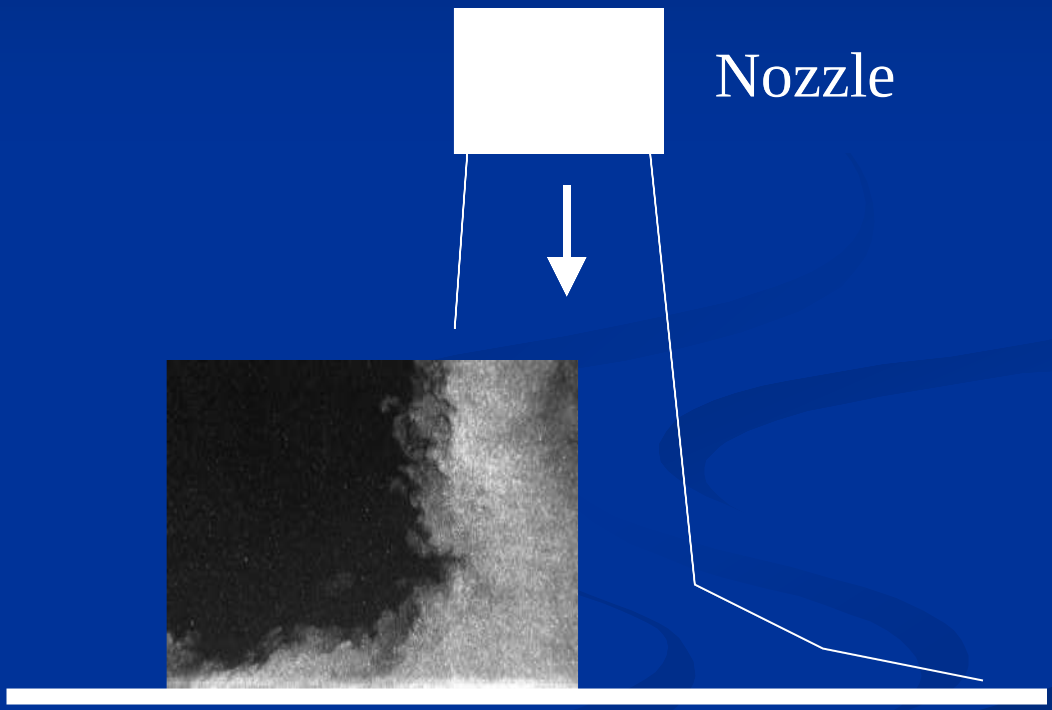
Cross-correlation to find velocity vector

PIV – Particle Imaging Velocimetry

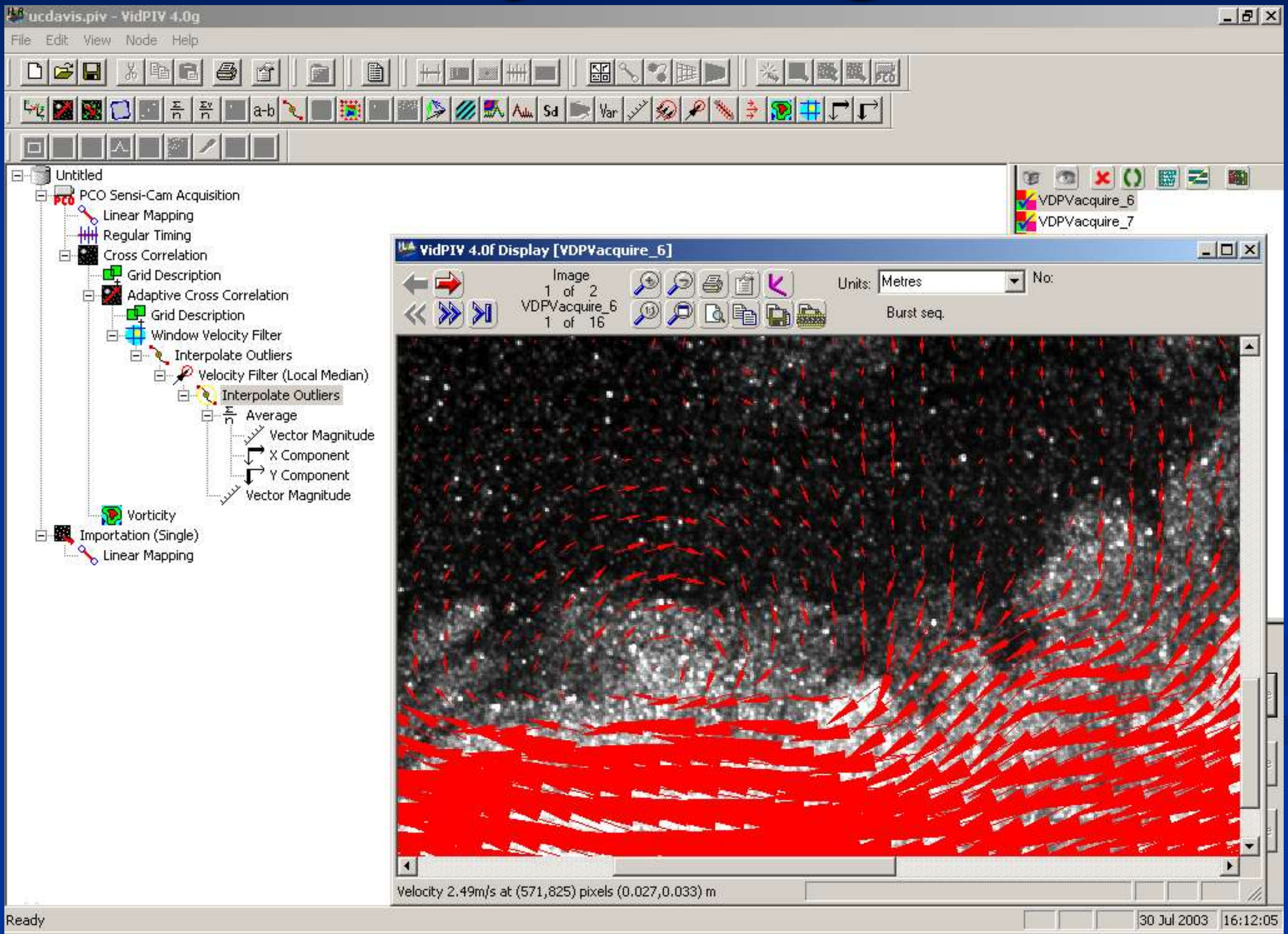
- A 2 component (2D) PIV system consisting of
  - Nd:Yag laser
  - PIV camera
  - Laser and camera synchroniser
  - Computer
  - PIV software

Experimental set-up cont.

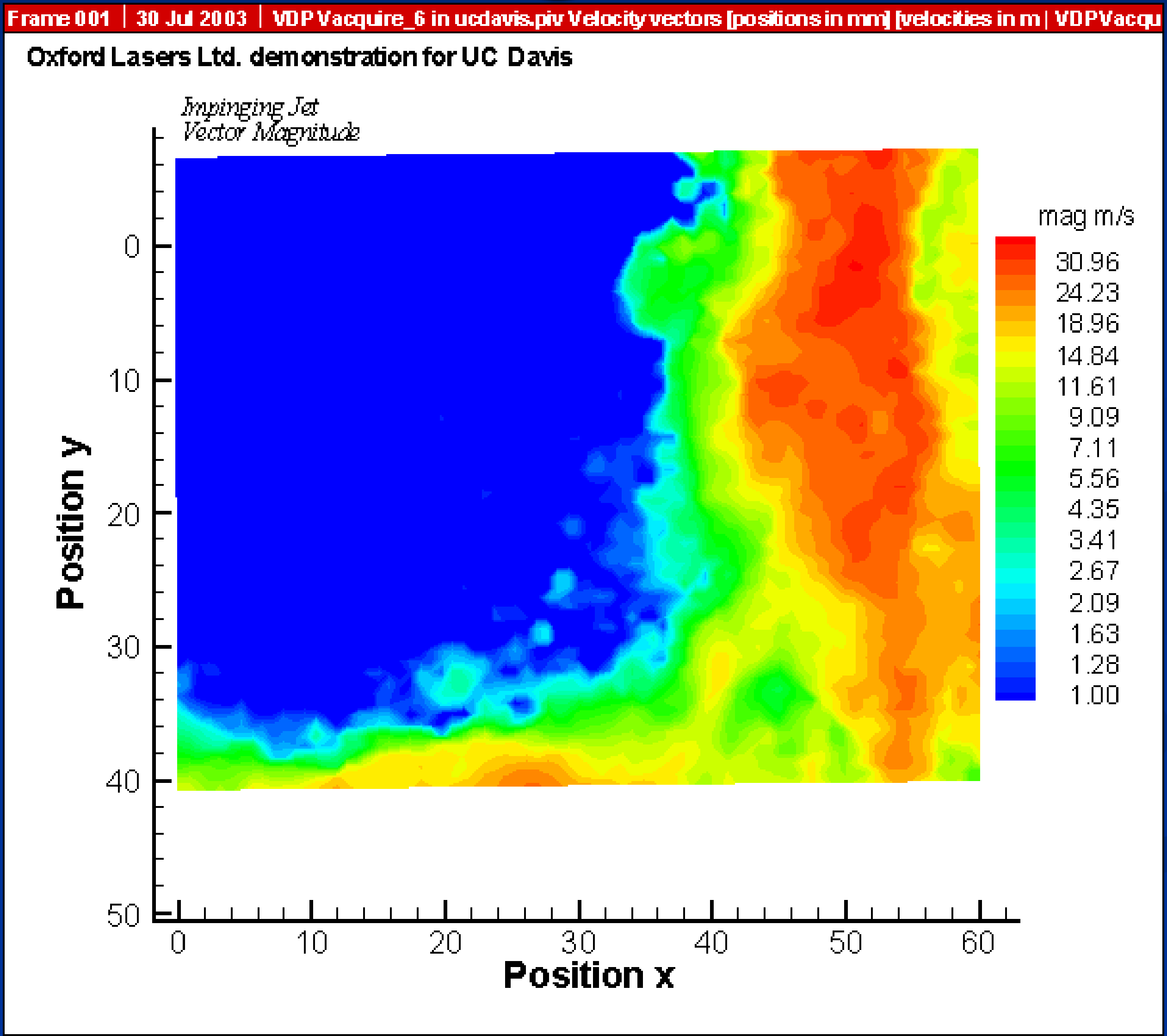
- Simple air jet directed at flat surface from a distance of approximately 120mm
- Seeding – incense smoke introduced to air intake (3 sticks)
- Field of view approx 50mm x 70mm
- Pulse separation 10µs
- 50mm f/1.4 Nikon lens
- Camera fitted with narrow band pass filter to allow operation in normal lighting conditions



Analyze images

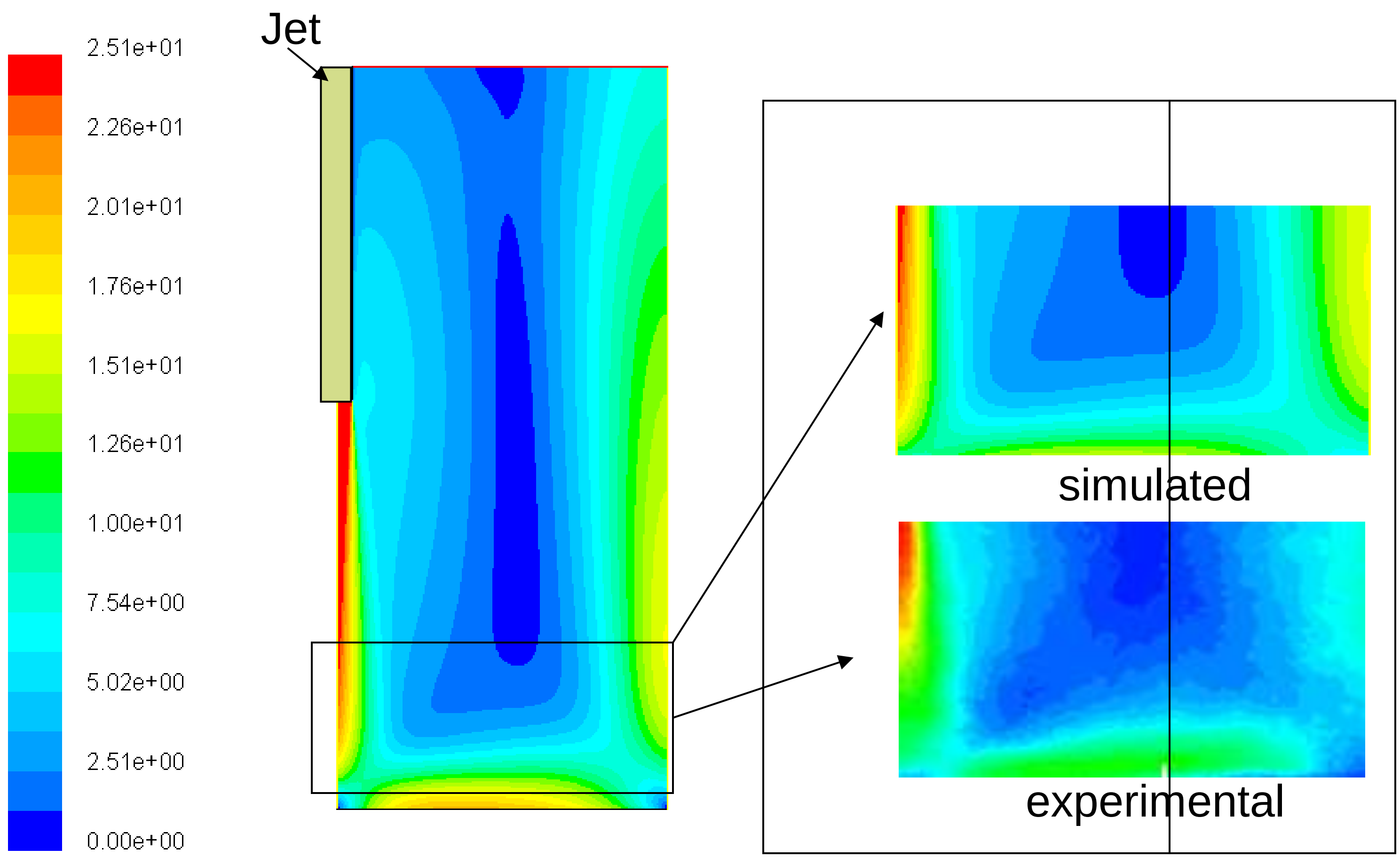


Results: Instantaneous vector magnitude

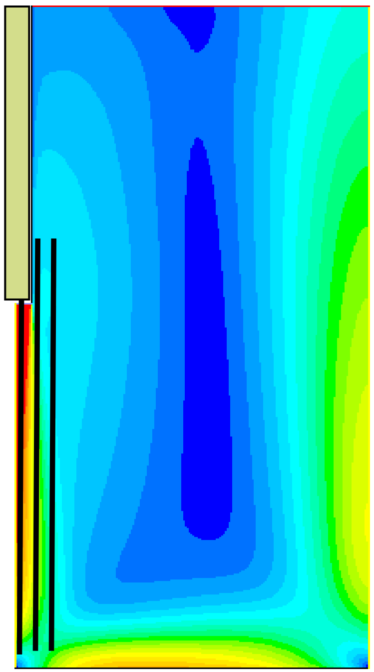


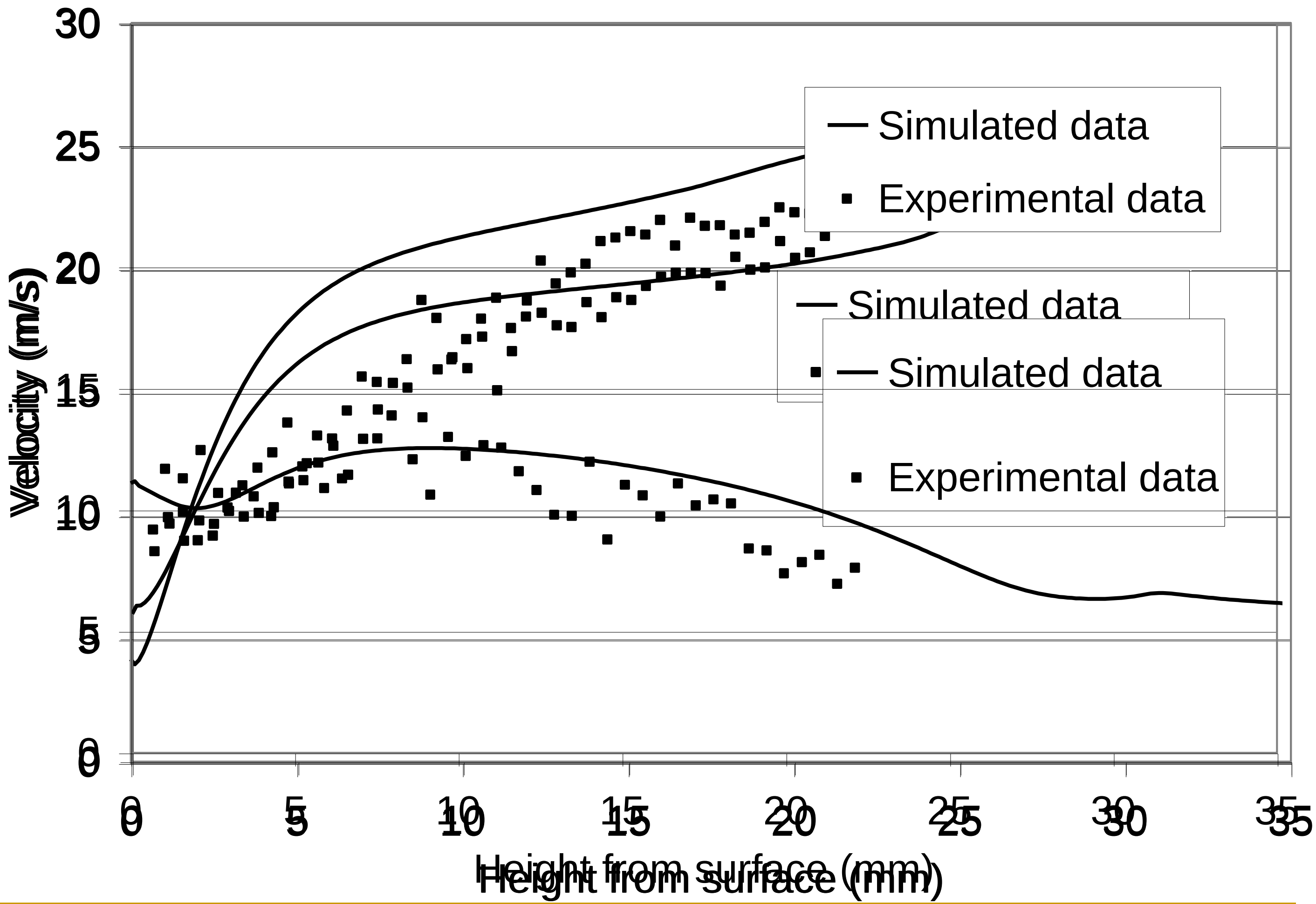
Video

PIV Results – Field Validation

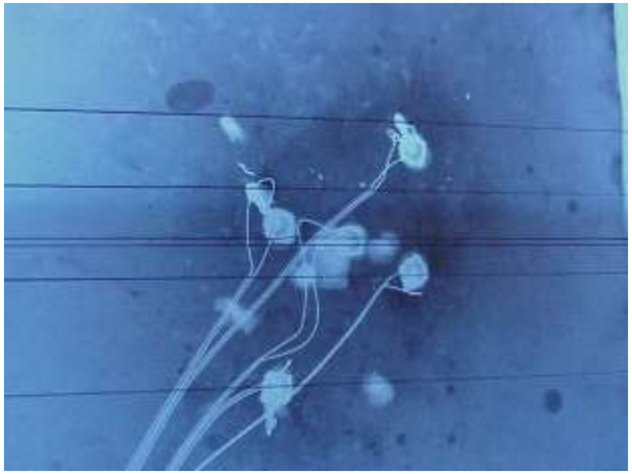


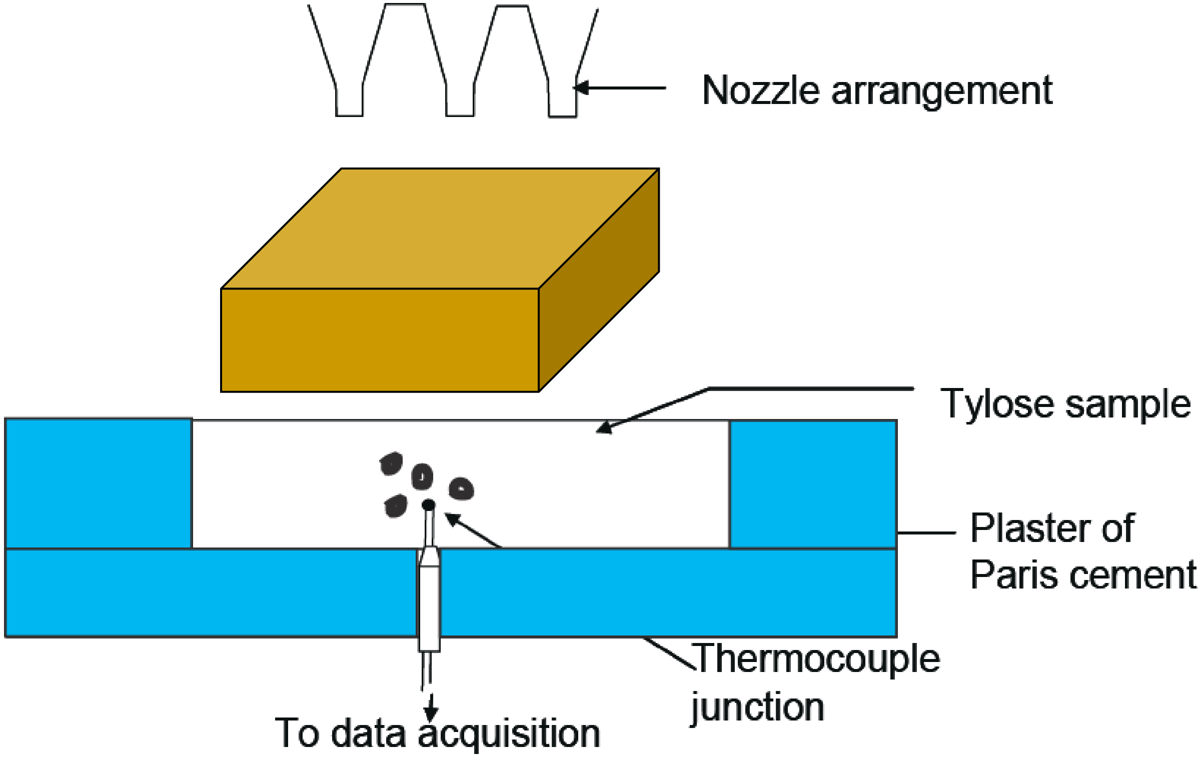
PIV Results – Line validation



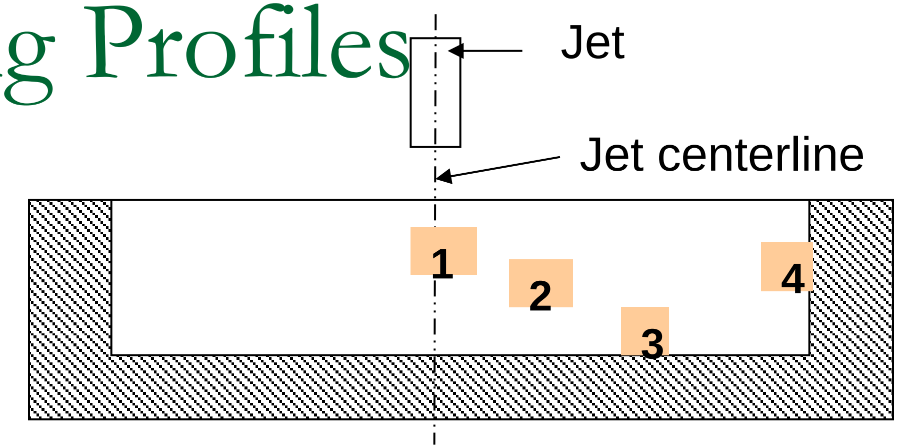


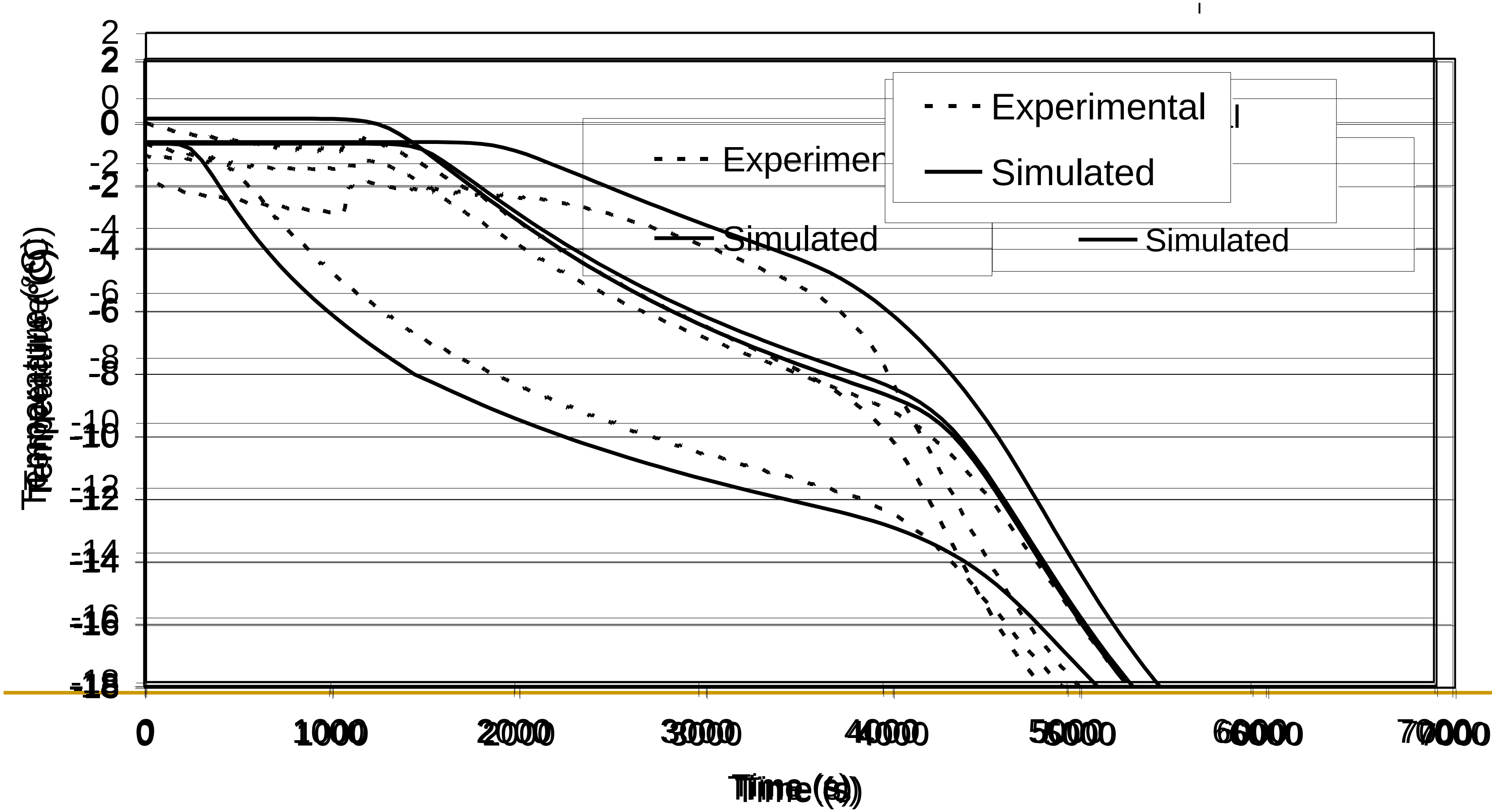
Heat Transfer Validation



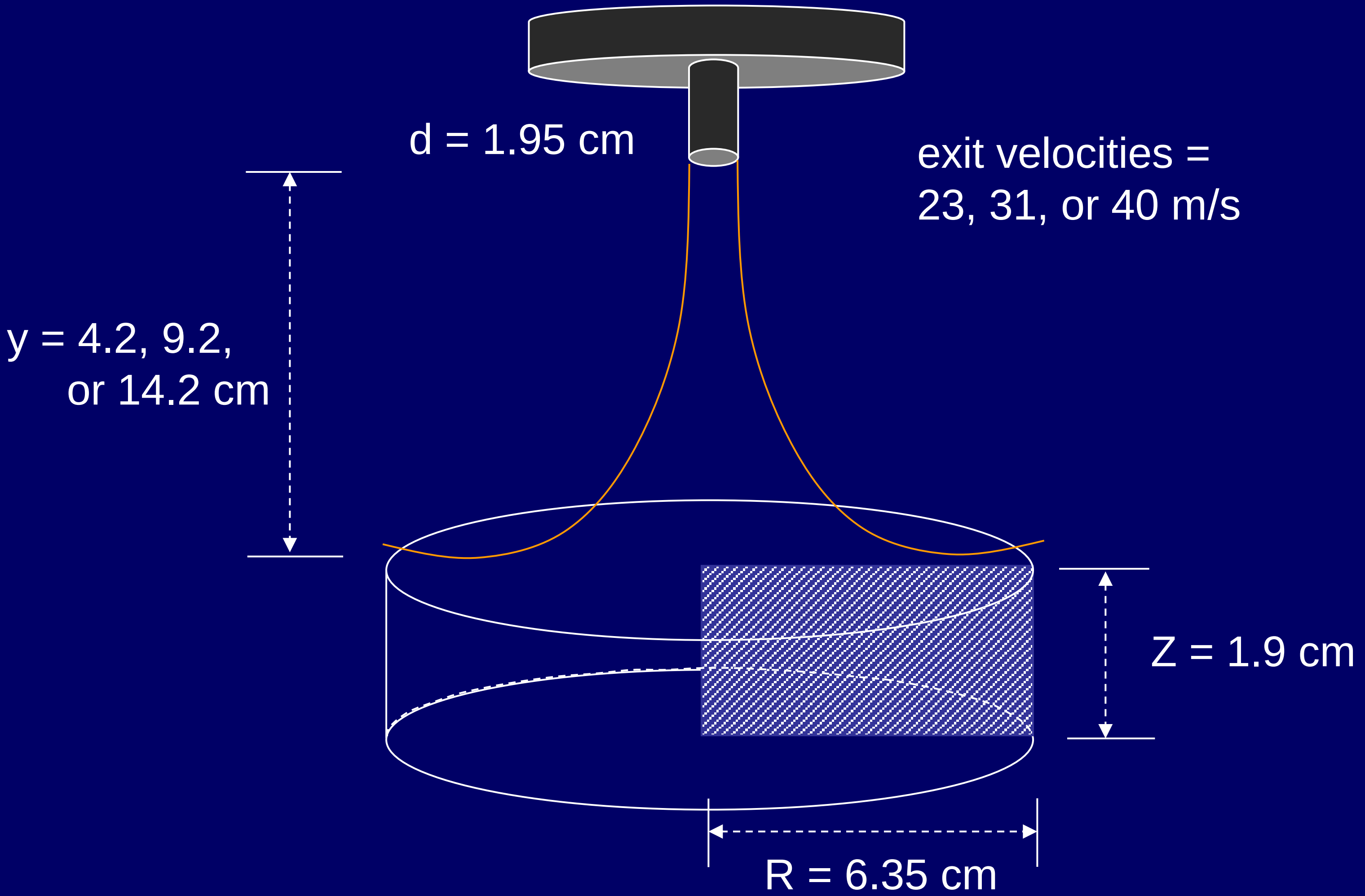


Validation – Freezing Profiles



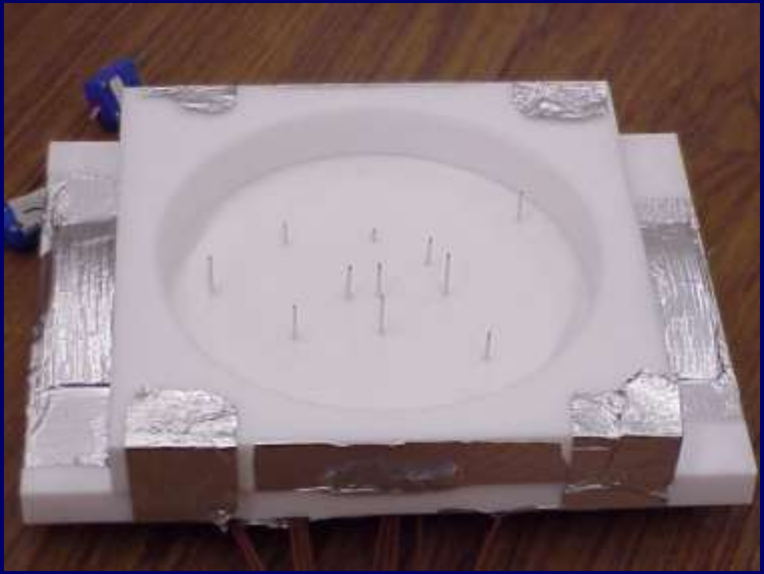


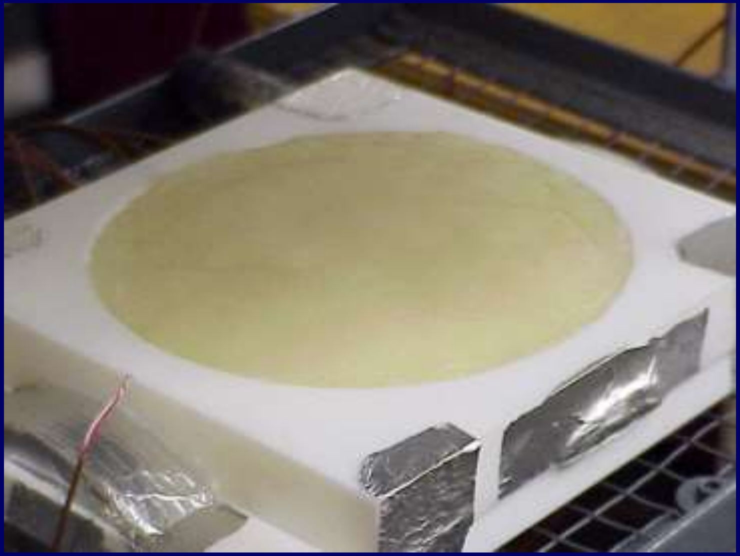
Impingement system for Thawing



Thawing Experiments with Tylose

- A mold was fabricated from Teflon to measure temperatures at various heights and radial positions in the Tylose sample 1.9 cm thick and 12.6 cm diameter
- Very fine thermocouples (44 gauge, type T) were used to measure temperatures
- Tylose was prepared and equilibrated in the mold prior to testing





Experimental vs. Predicted Temperatures

- Experimental temperatures matched well with predicted results
  - Predicted times for the product to reach 0°C matched within 10% of the experimental data 65% of the time

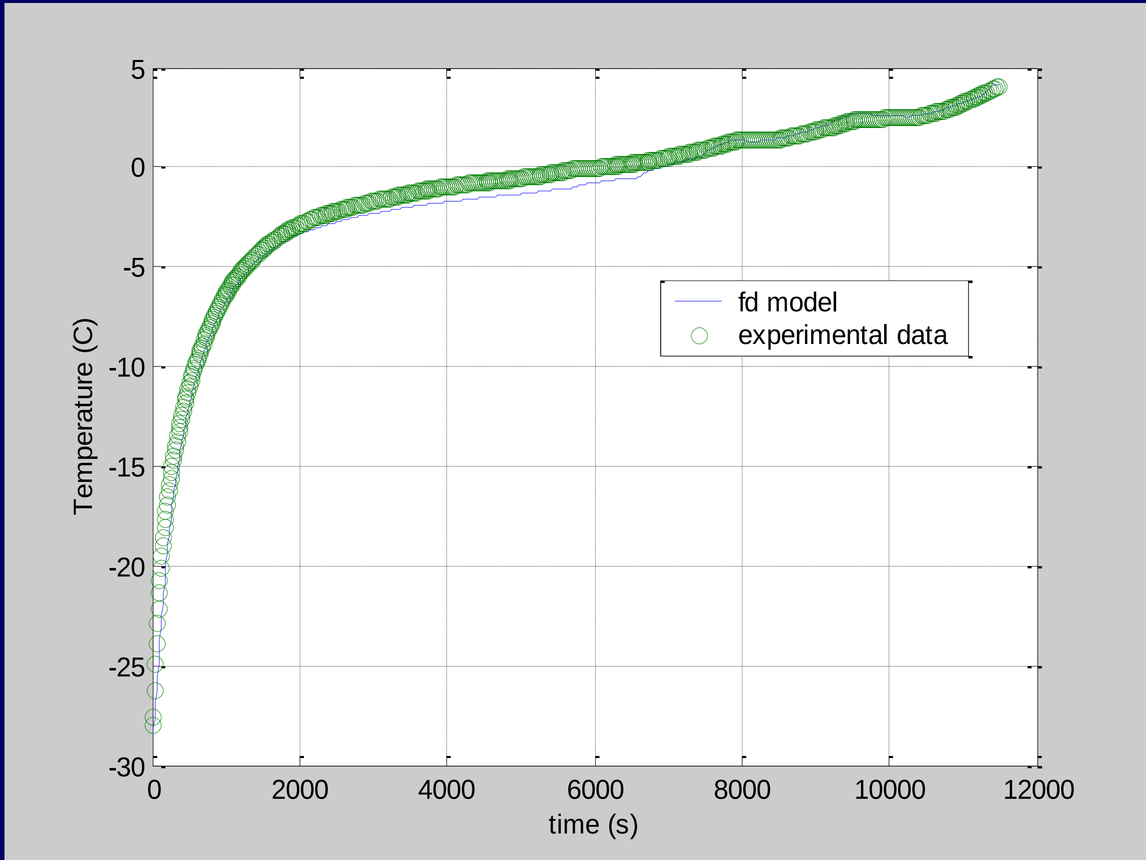
<u>Time to reach 0°C</u>

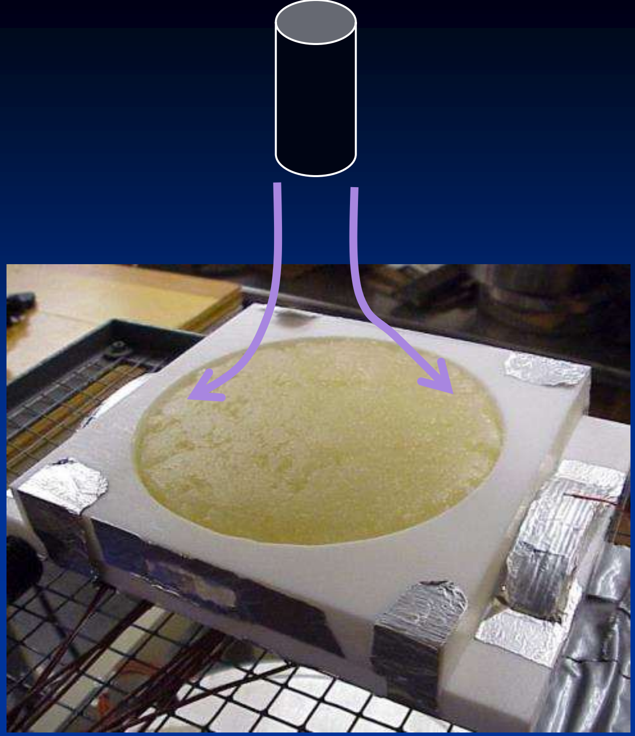
Predicted = 115 min

Experimental = 102 min

Difference = 13.3%

RMSE = 0.6°C





<u>Thawing Times</u> <u>(1.9 cm thick Tylose) from -20 C to 0 C</u>

- Refrigerator (5°C, h=5.5 W/m^2K) : 30 hours
- Laboratory incubator (5°C, h=12 W/m^2K) : 14 hours
- Laboratory incubator (12°C, h=12 W/m^2K) : 5 hours
- A single air impingement jet (6°C) : <2 hours

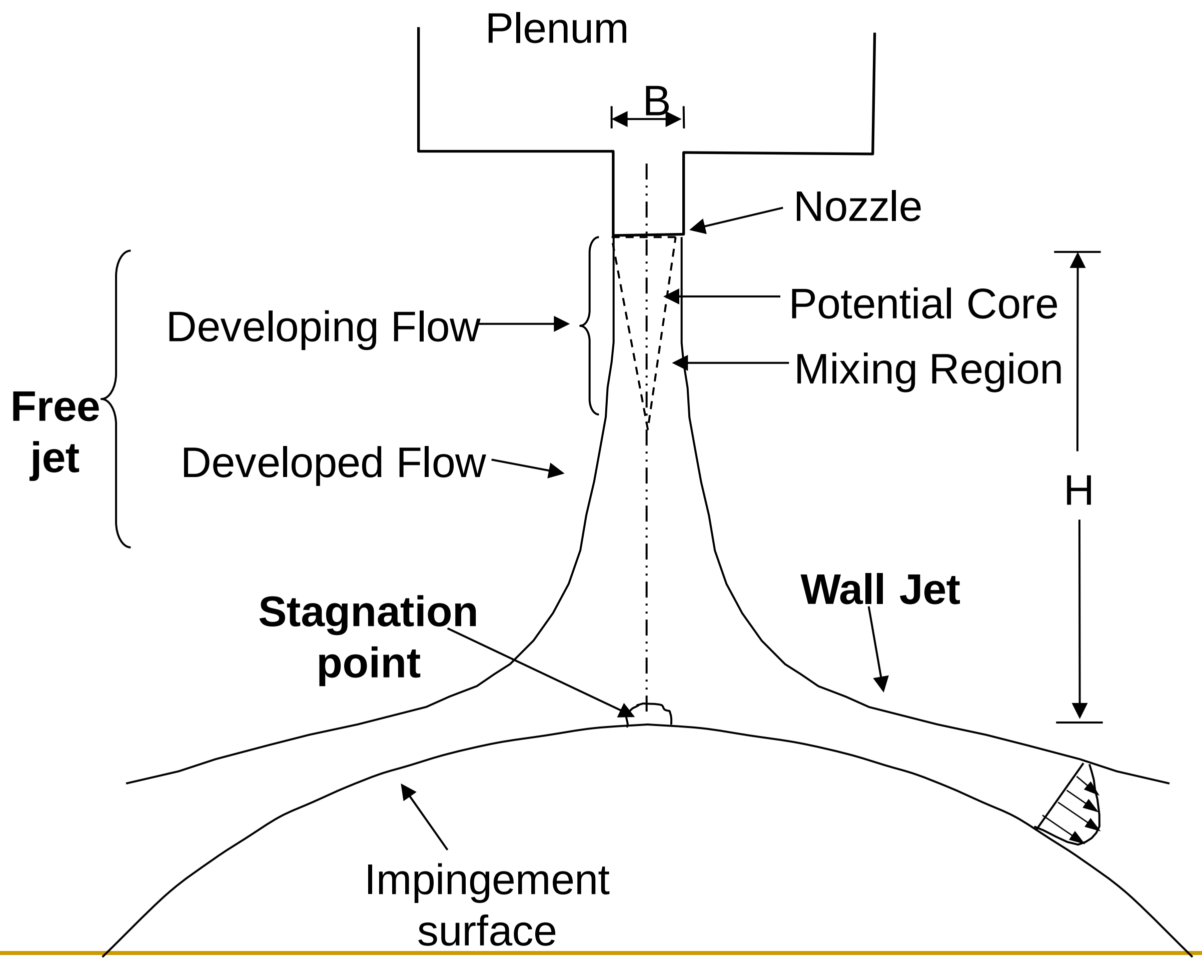
Additional experiments with Bratwurst

- Packaged bratwurst were thawed using the impingement system
- Air velocity = 40 m/s; z = 4.2 cm

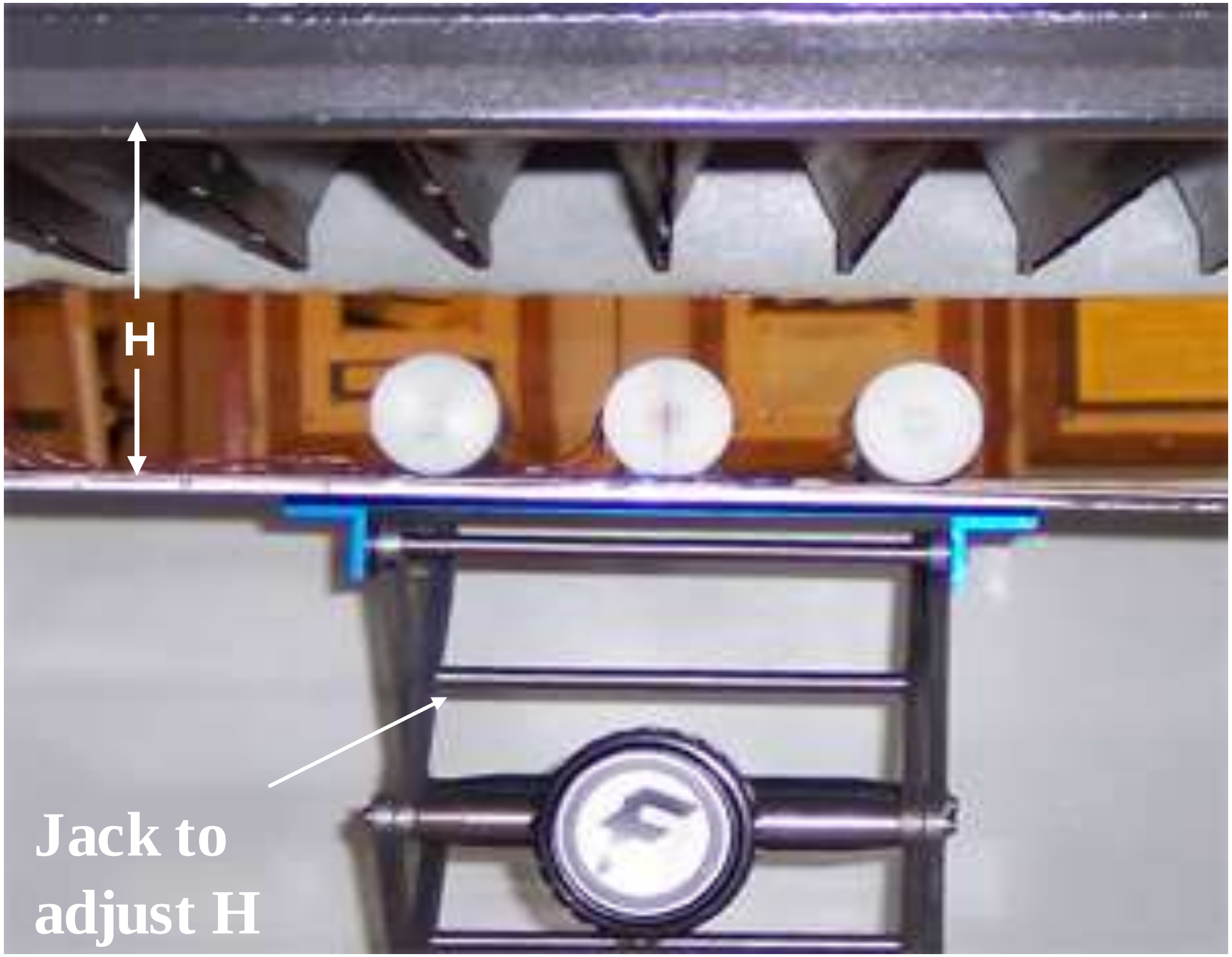
Thawing time for Bratwurst

No Impingement	Time to reach 0°C (min)	Standard deviation (min)
Original Package	448	30
Individually wrapped with aluminum foil	339	8
Impingement		
Original package	192	14
Individually wrapped with aluminum foil	65	10

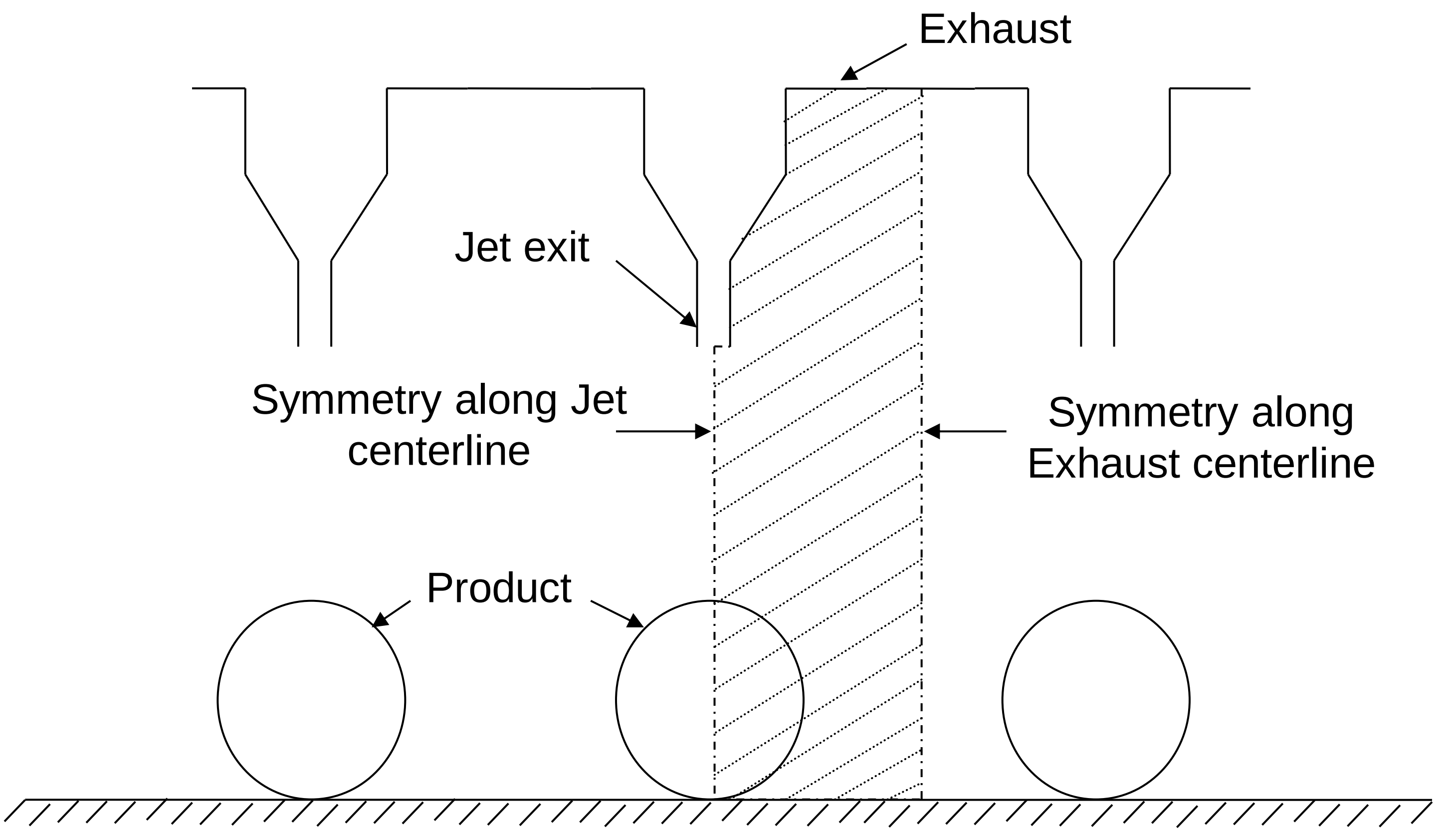
Fluid flow around a cylindrical object under air jet impingement



Modeling Our System



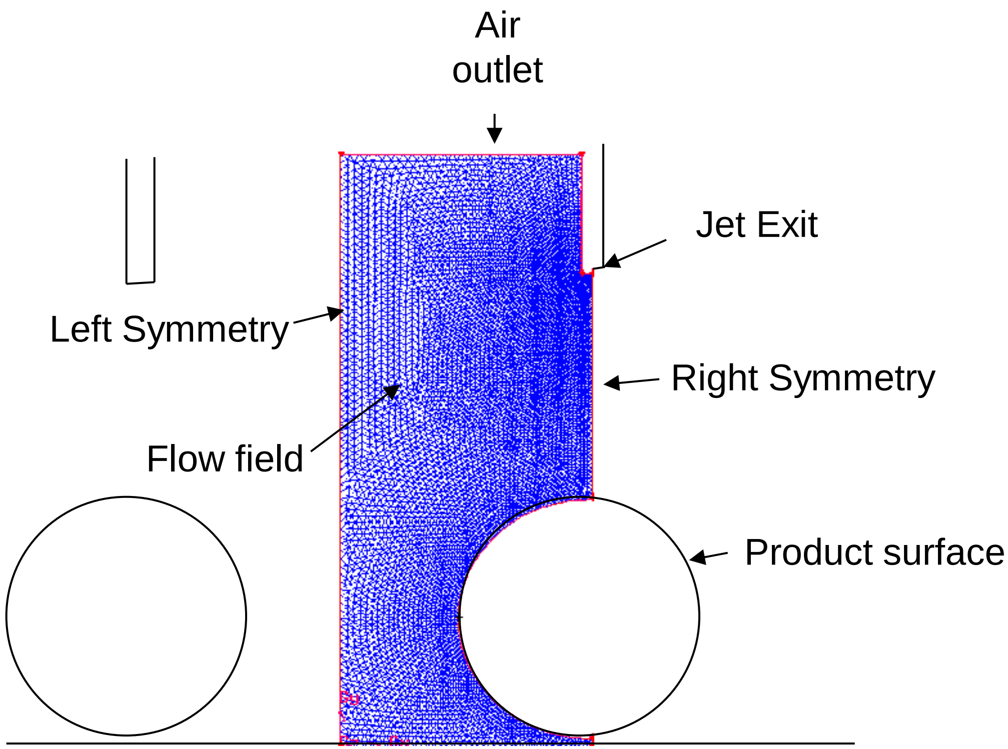
System Model : The Computational Domain



Flow and heat transfer simulations: FLUENT (CFD)

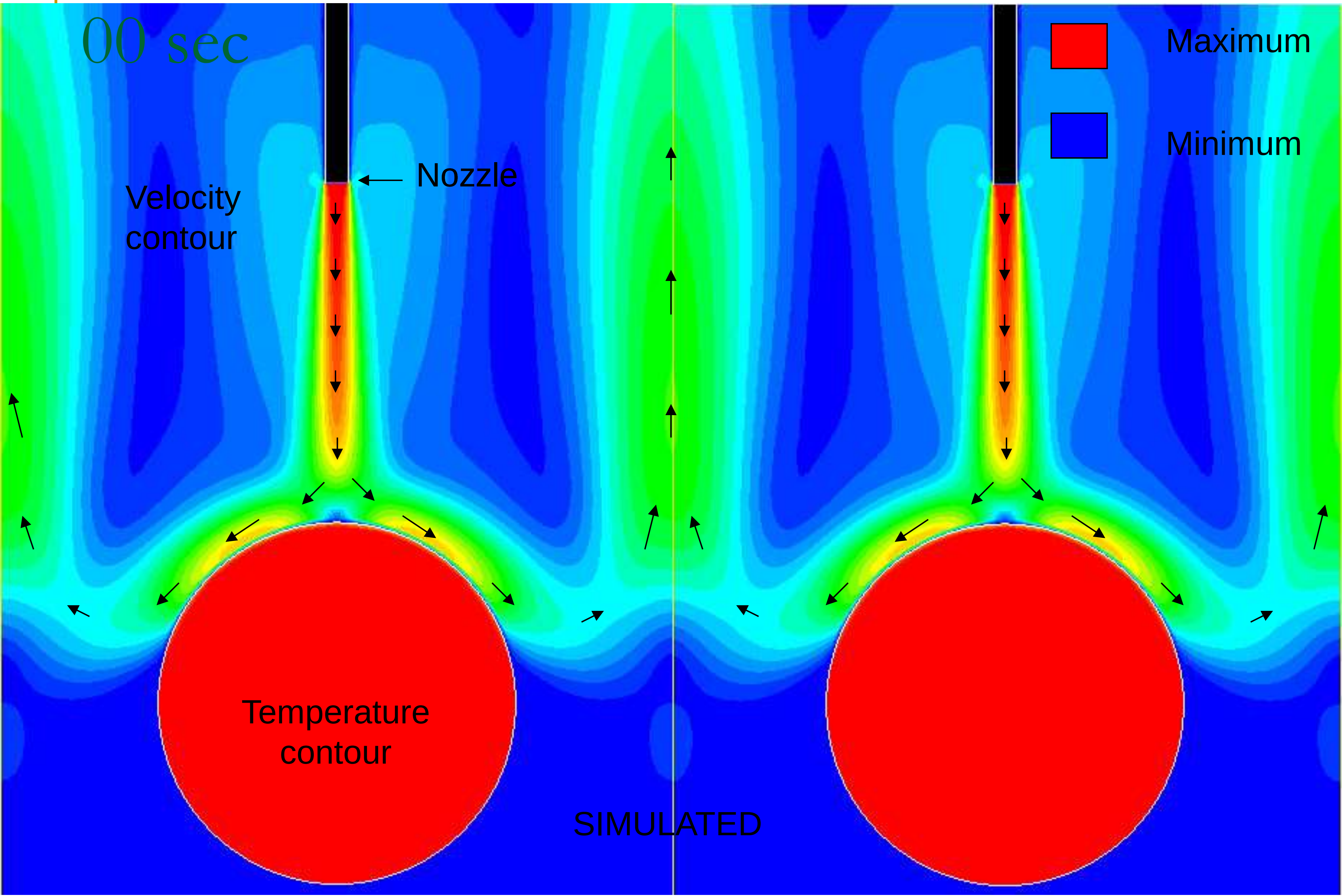
Computational domain: axi-symmetrical about the jet centerline

Heat transfer was solved using **κ-ε turbulence model**.

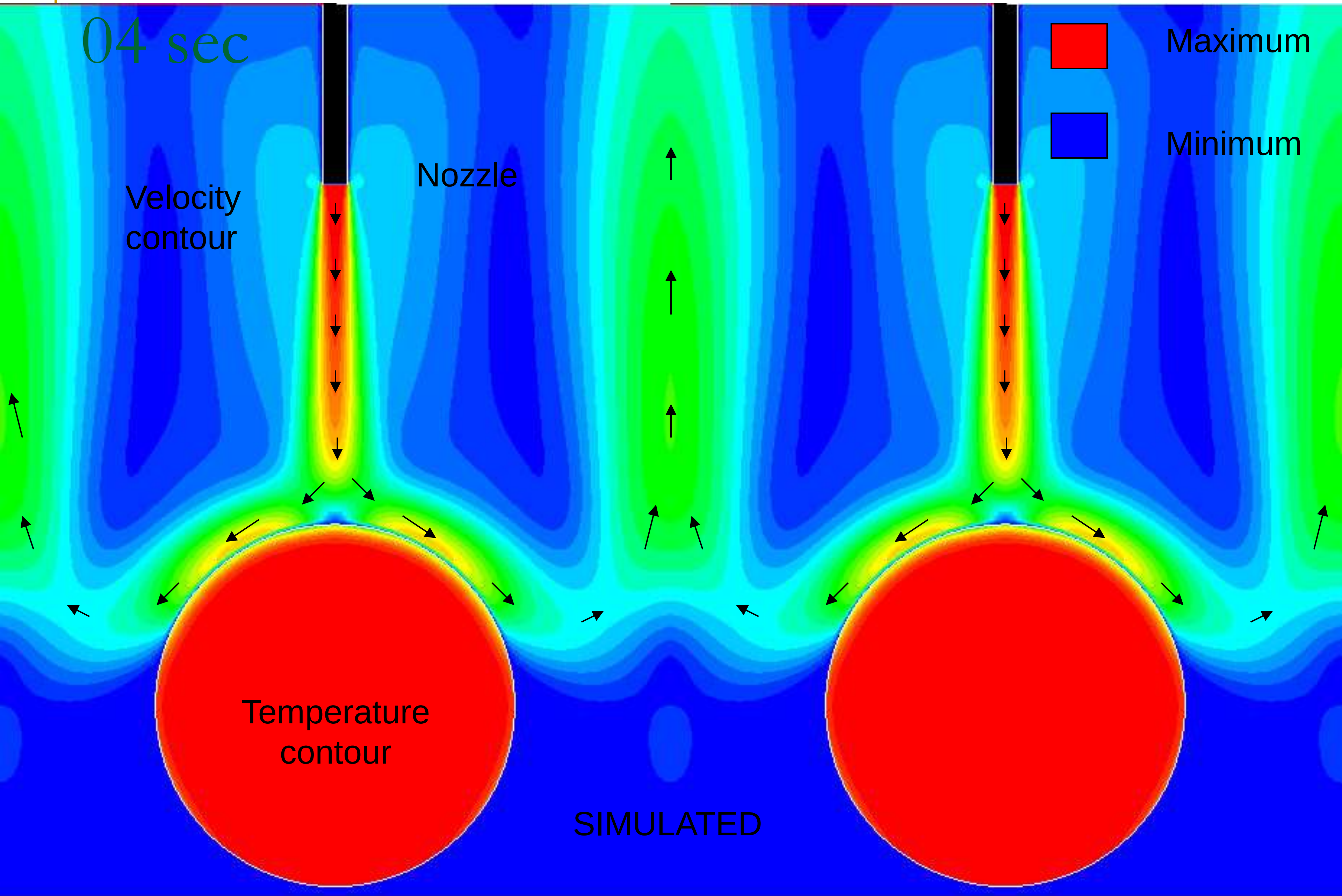


Axi-symmetric computational domain

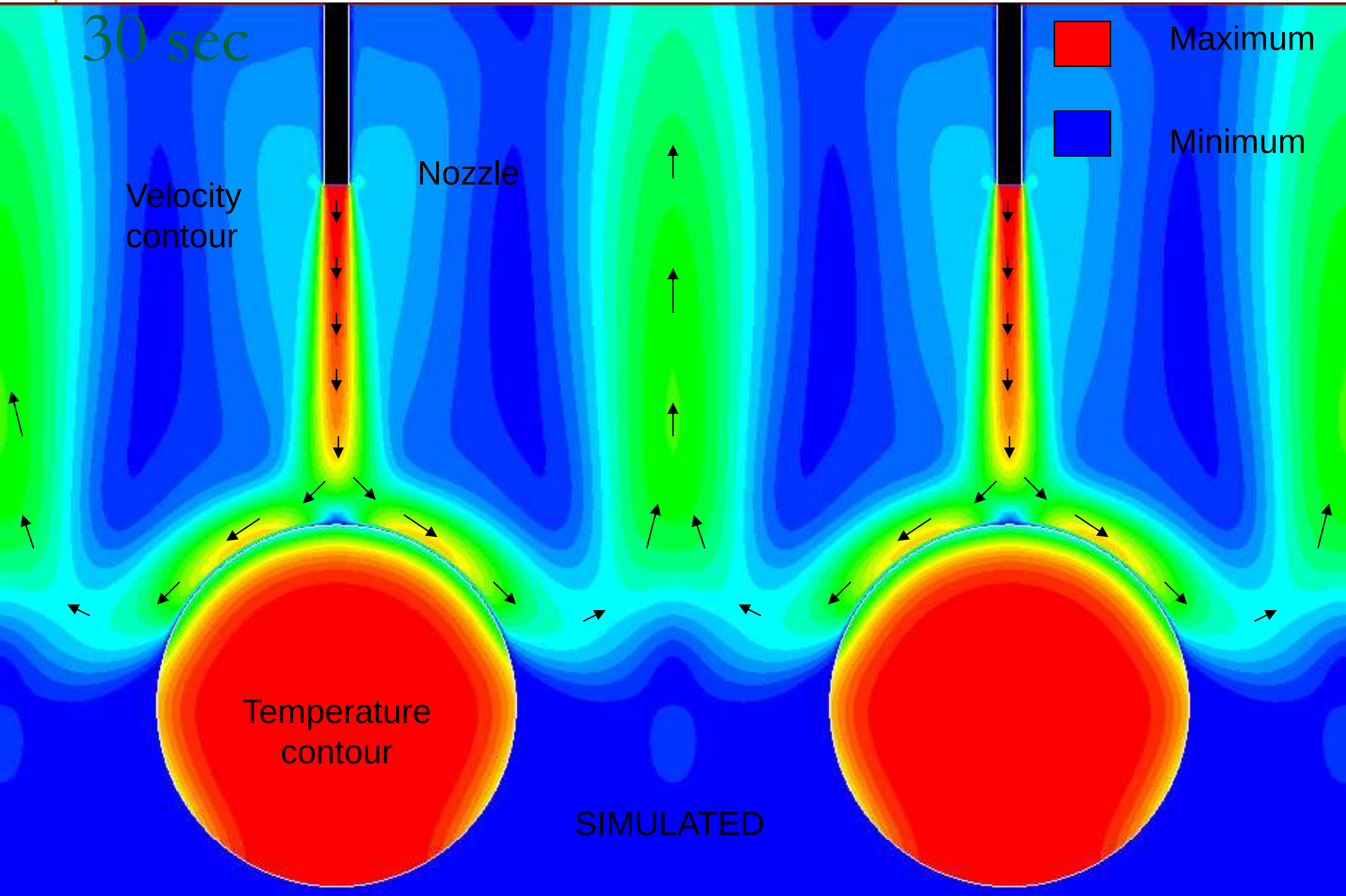
Contour outside the circle is velocity contour and that inside is temperature contour



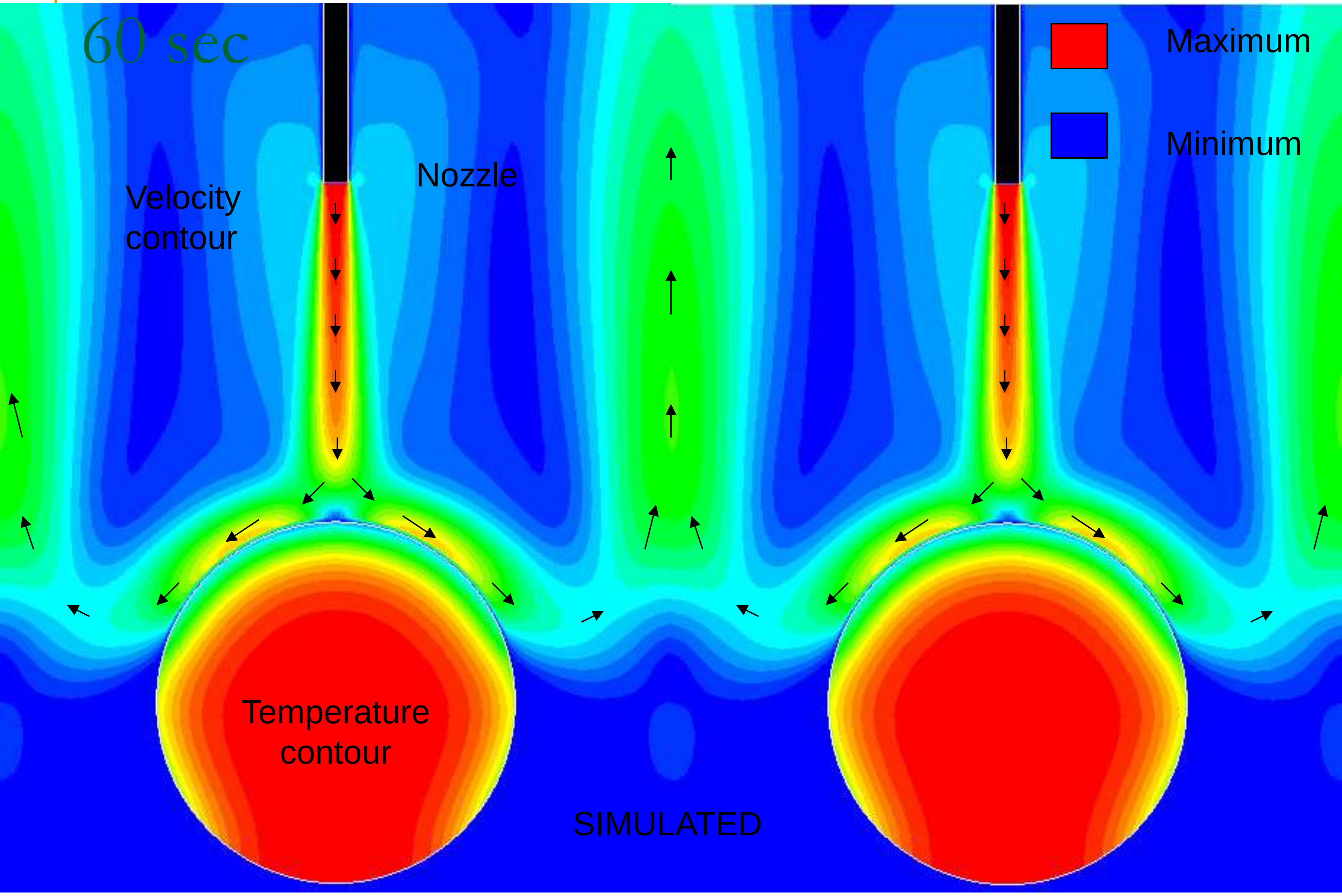
Contour outside the circle is velocity contour and that inside is temperature contour



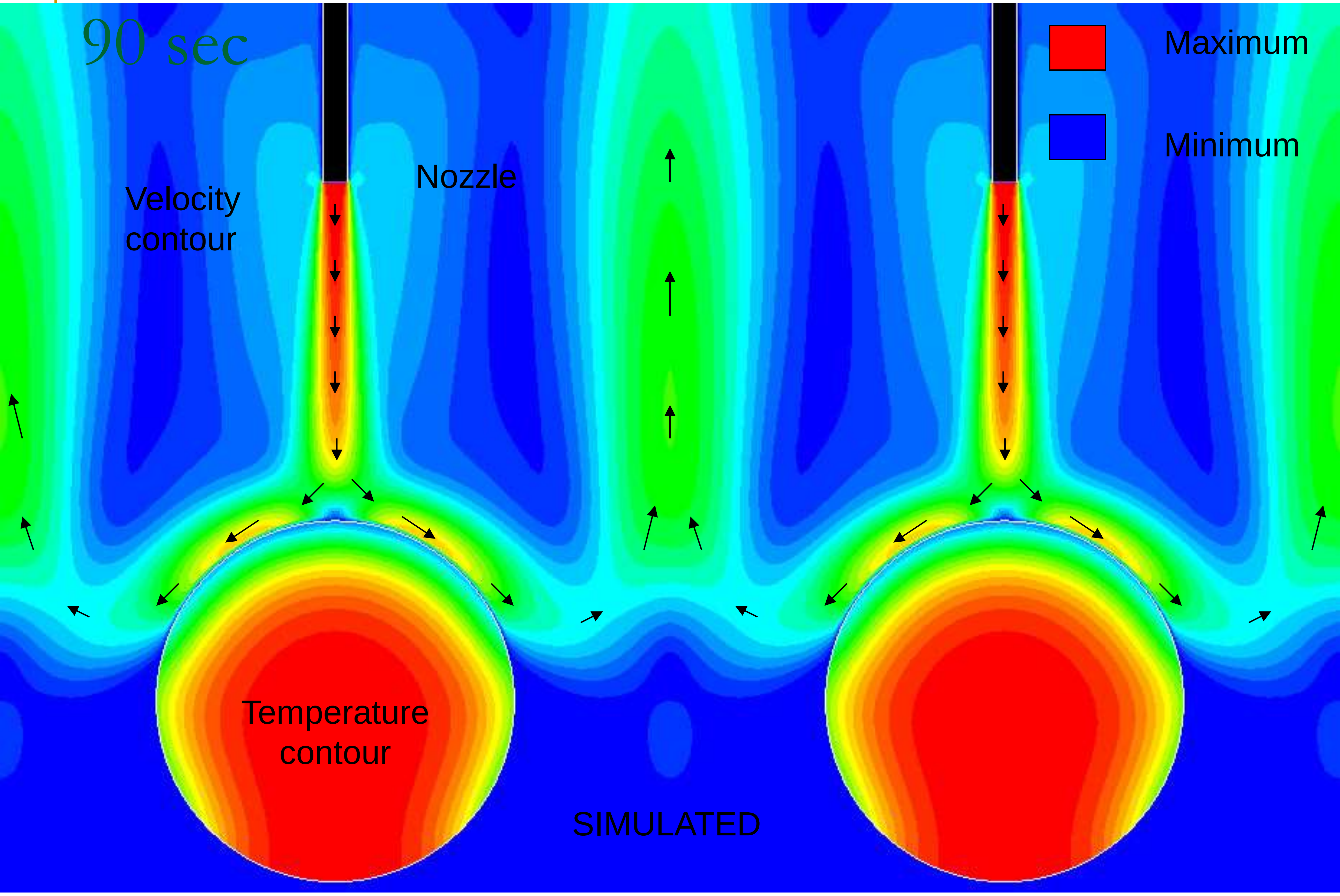
Contour outside the circle is velocity contour and that inside is temperature contour



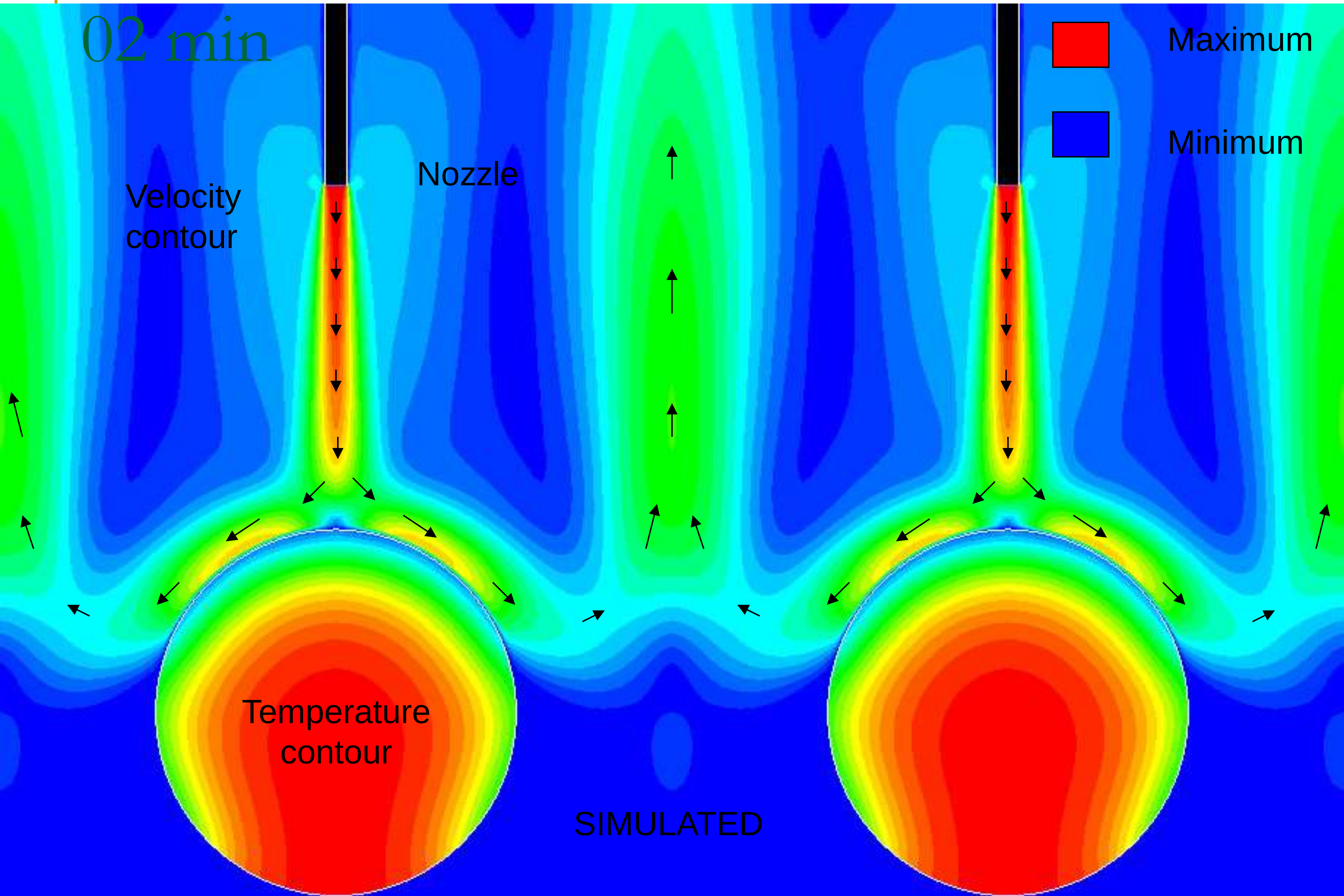
Contour outside the circle is velocity contour and that inside is temperature contour



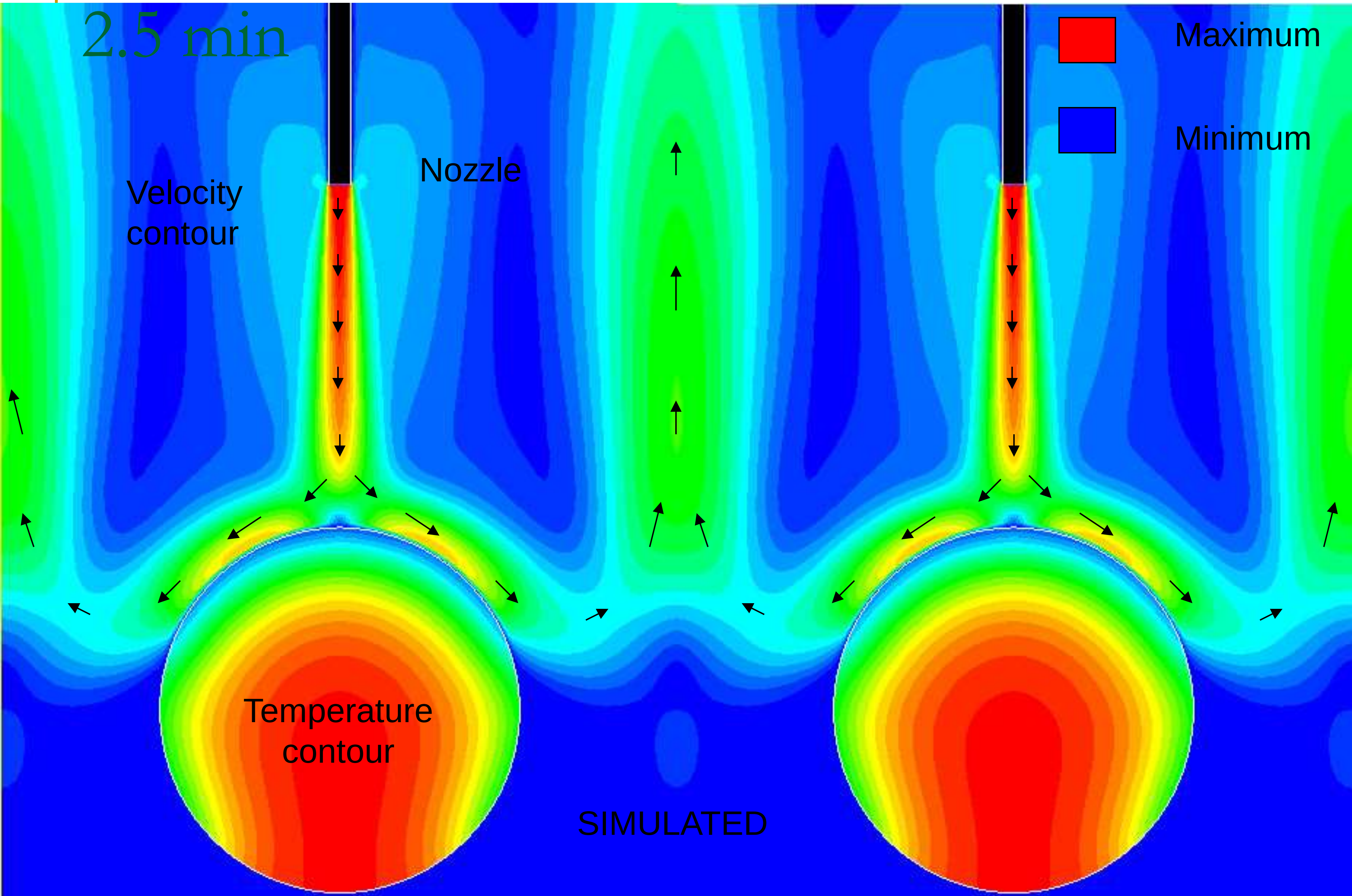
Contour outside the circle is velocity contour and that inside is temperature contour



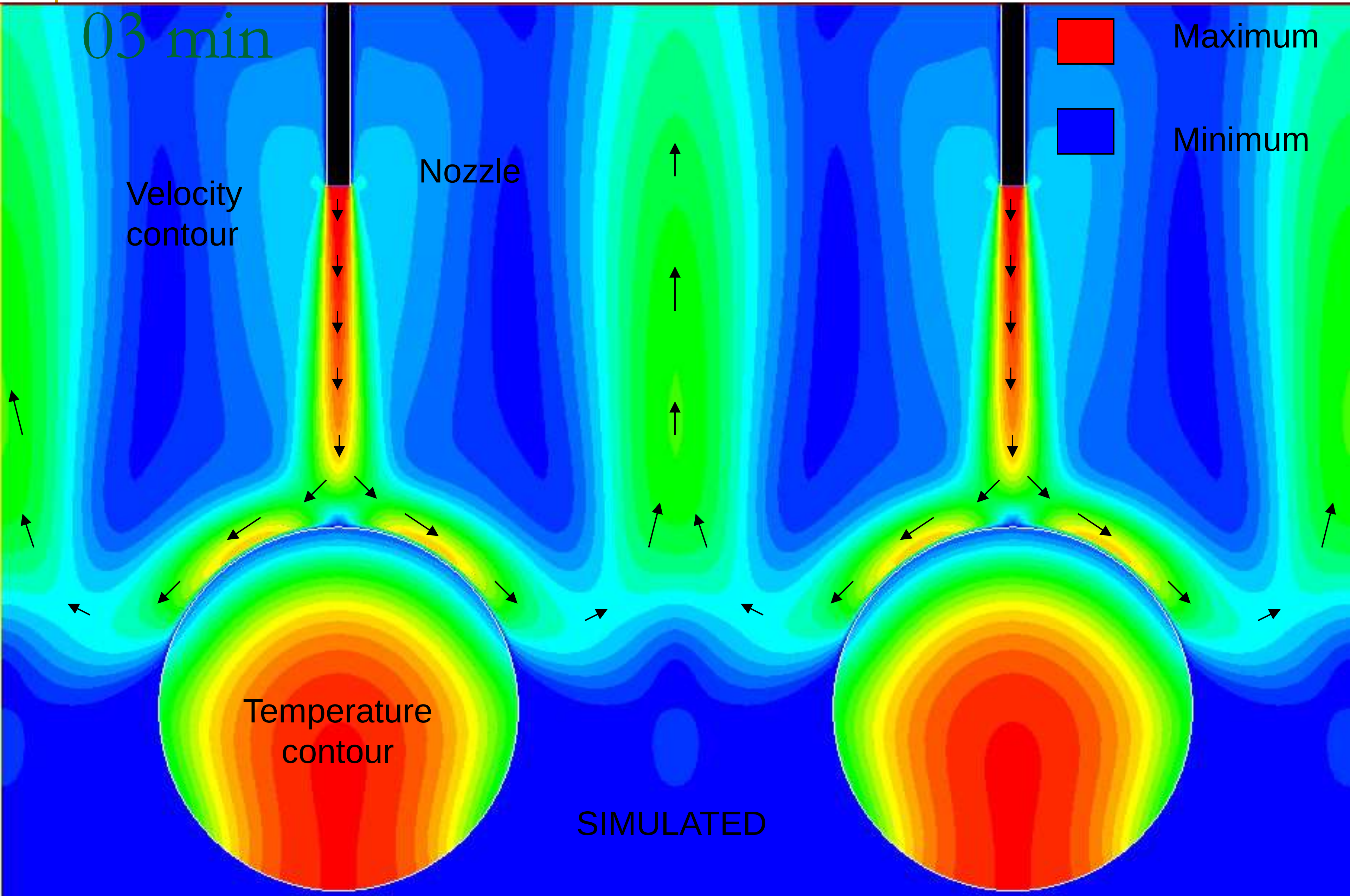
Contour outside the circle is velocity contour and that inside is temperature contour



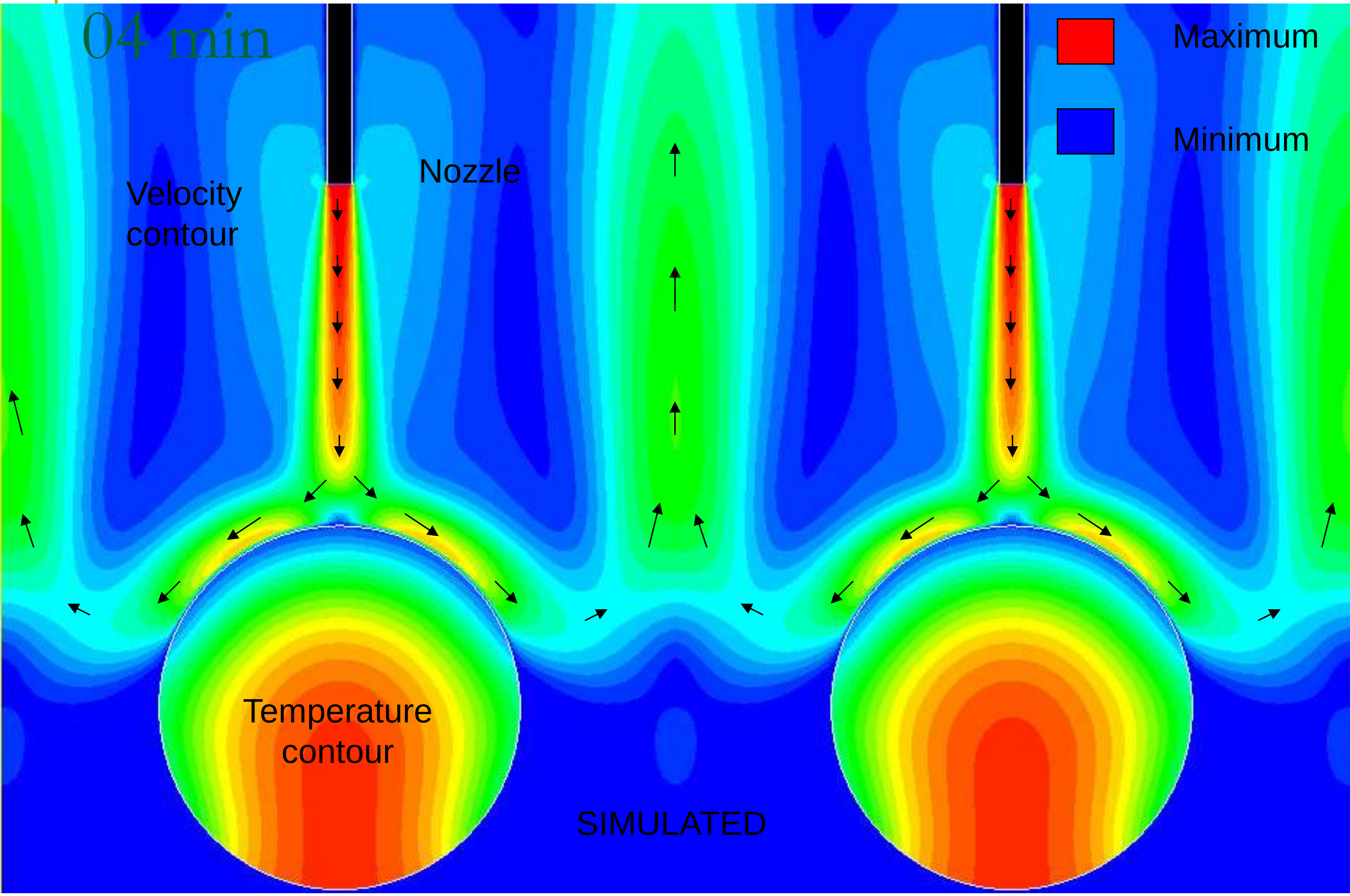
Contour outside the circle is velocity contour and that inside is temperature contour



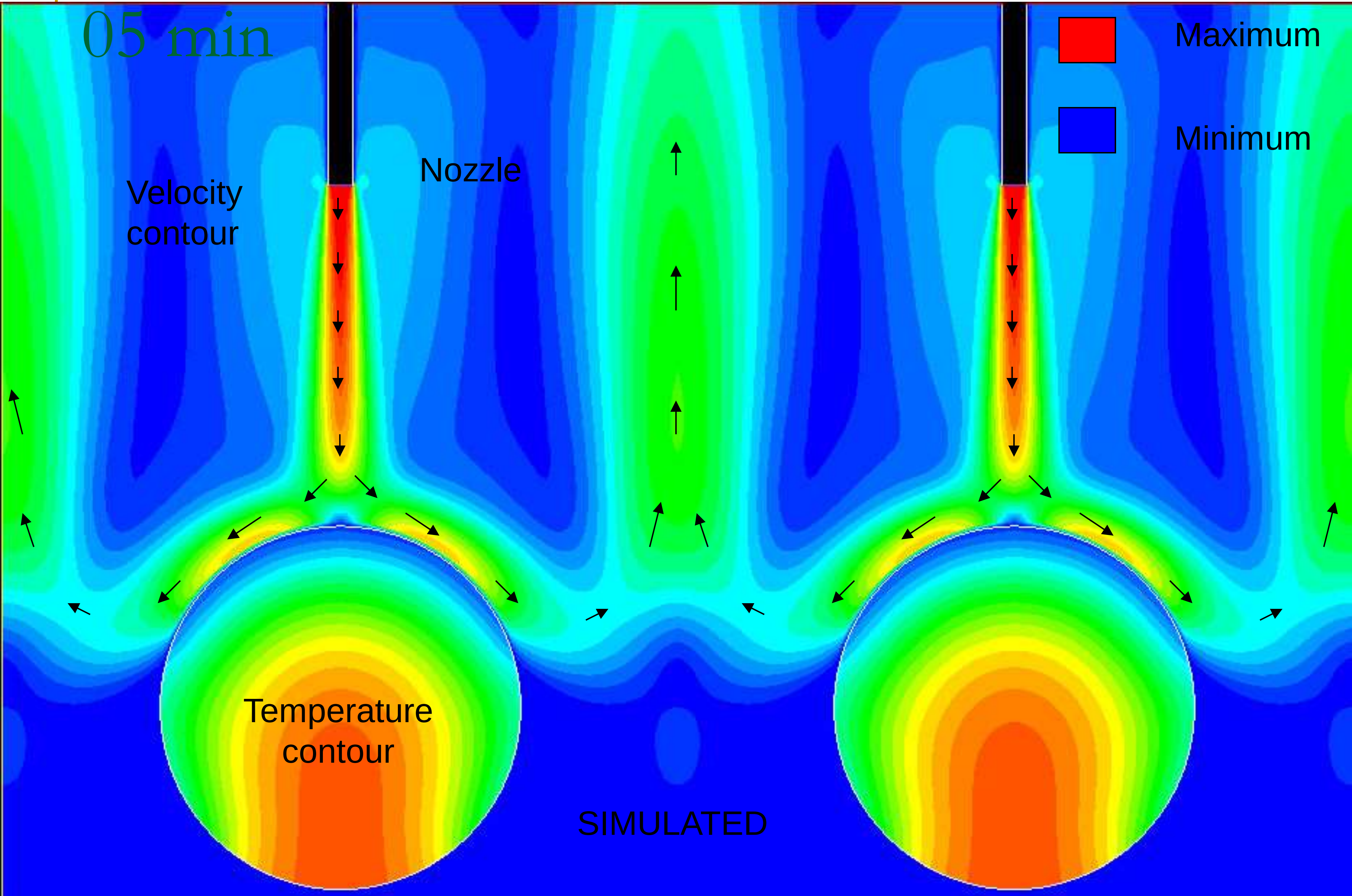
Contour outside the circle is velocity contour and that inside is temperature contour



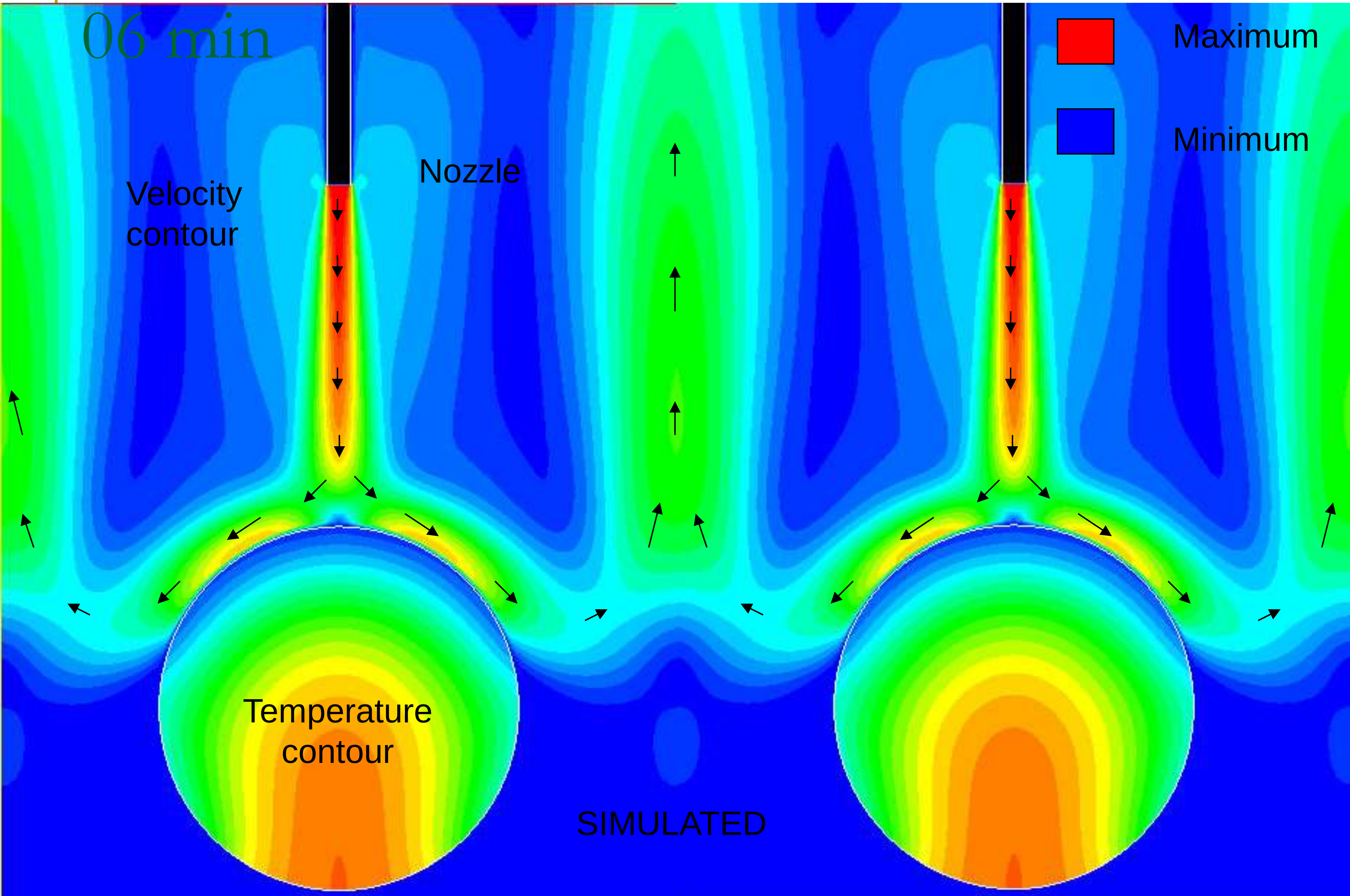
Contour outside the circle is velocity contour and that inside is temperature contour



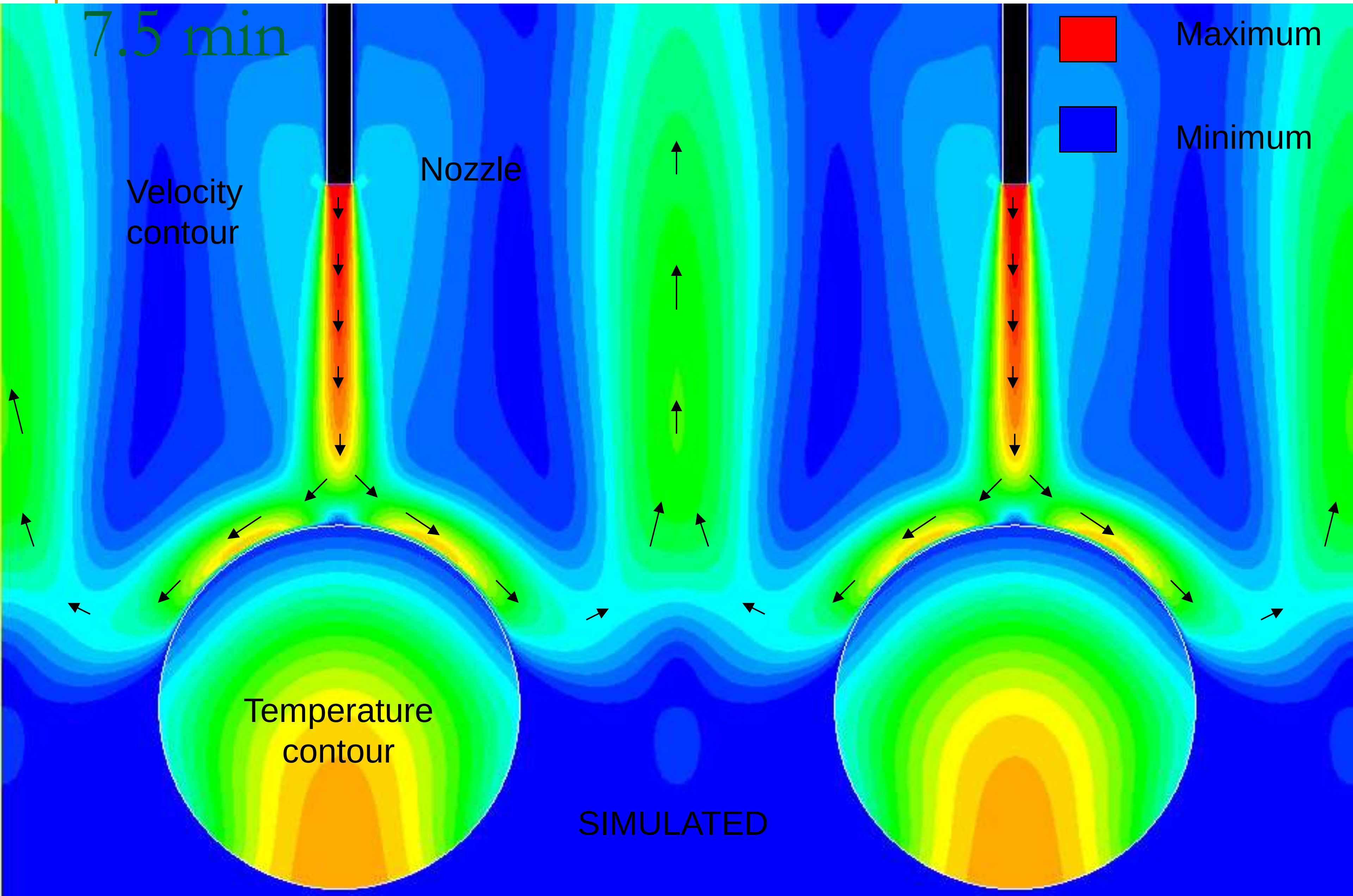
Contour outside the circle is velocity contour and that inside is temperature contour



Contour outside the circle is velocity contour and that inside is temperature contour



Contour outside the circle is velocity contour and that inside is temperature contour



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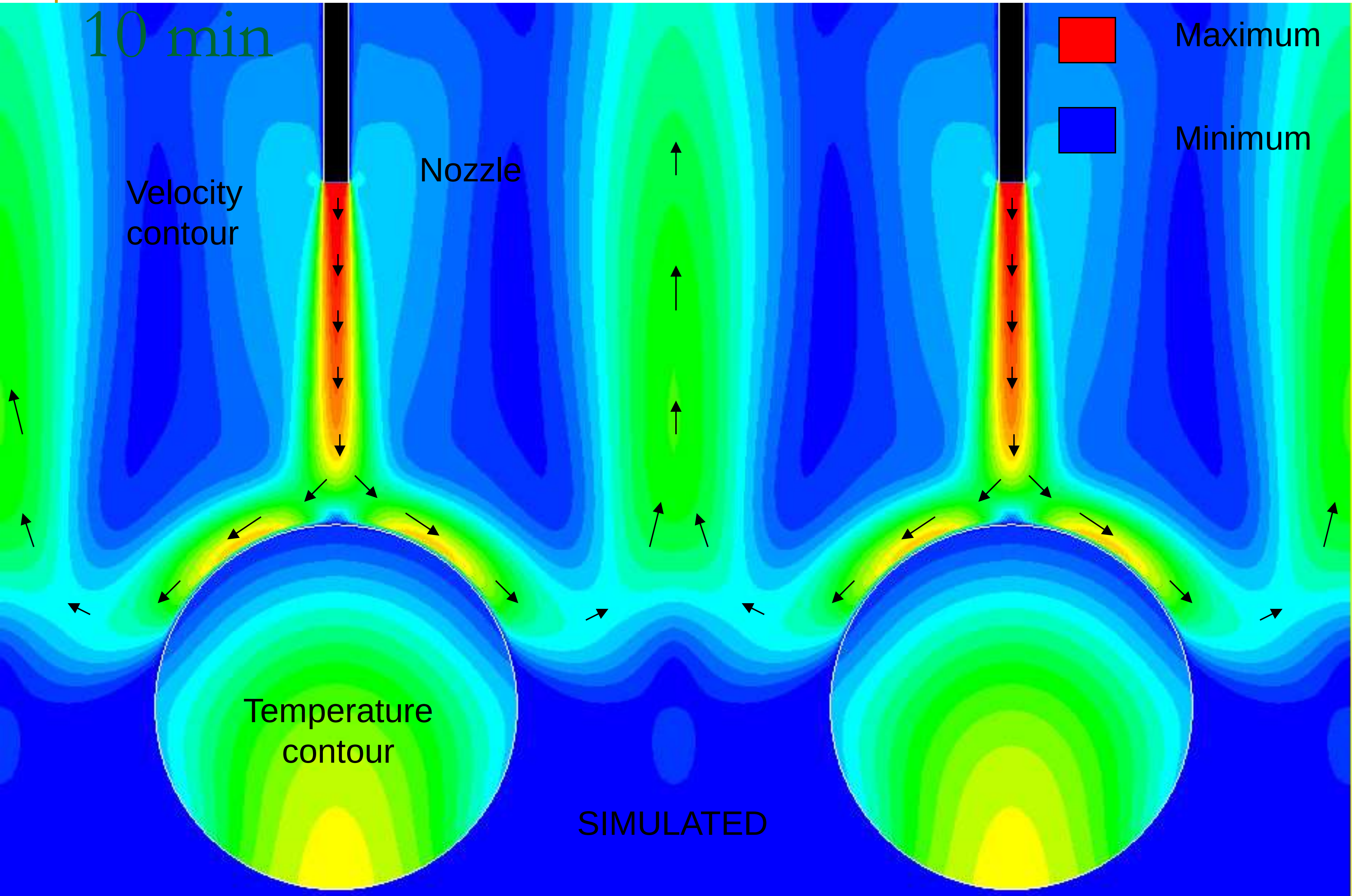

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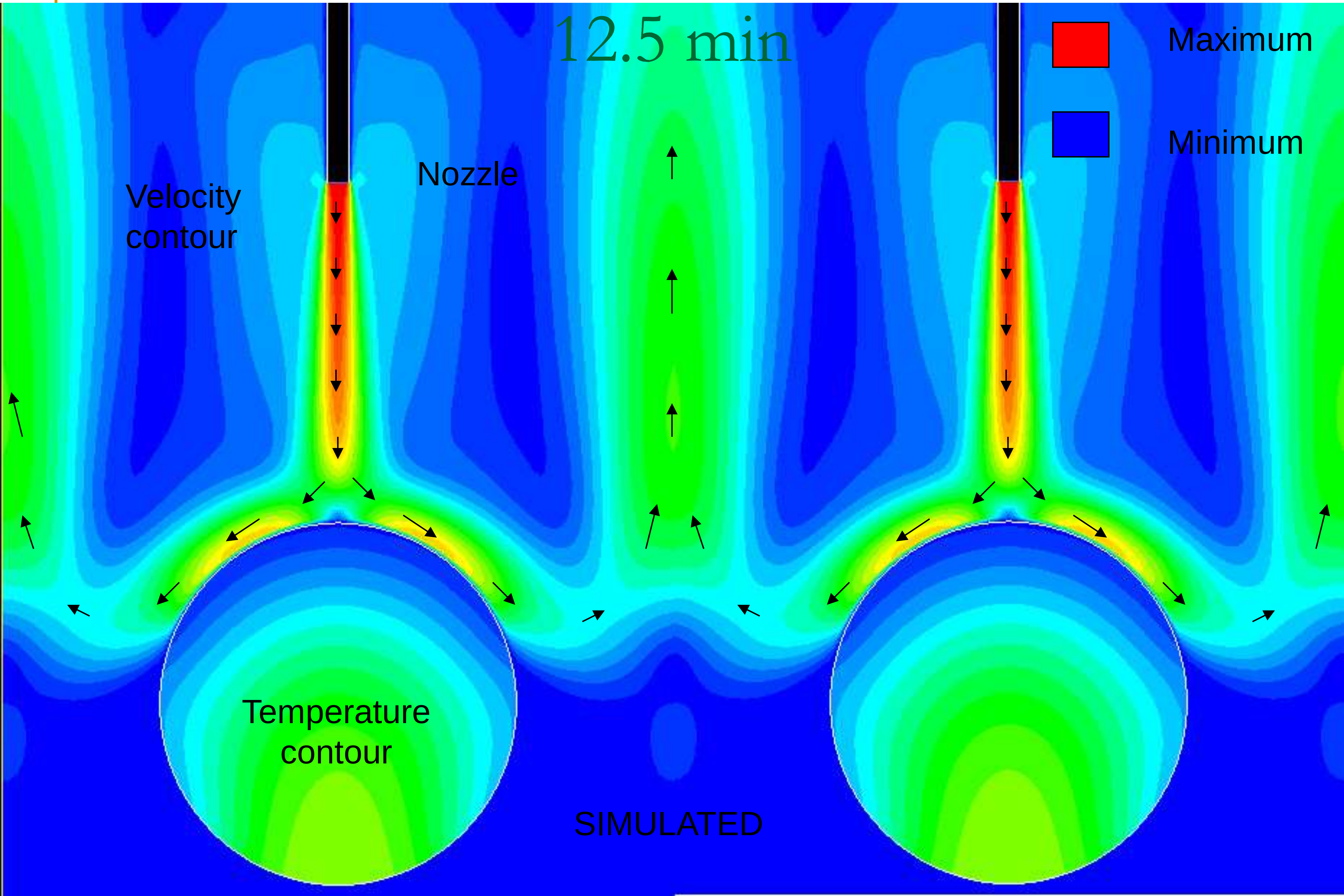

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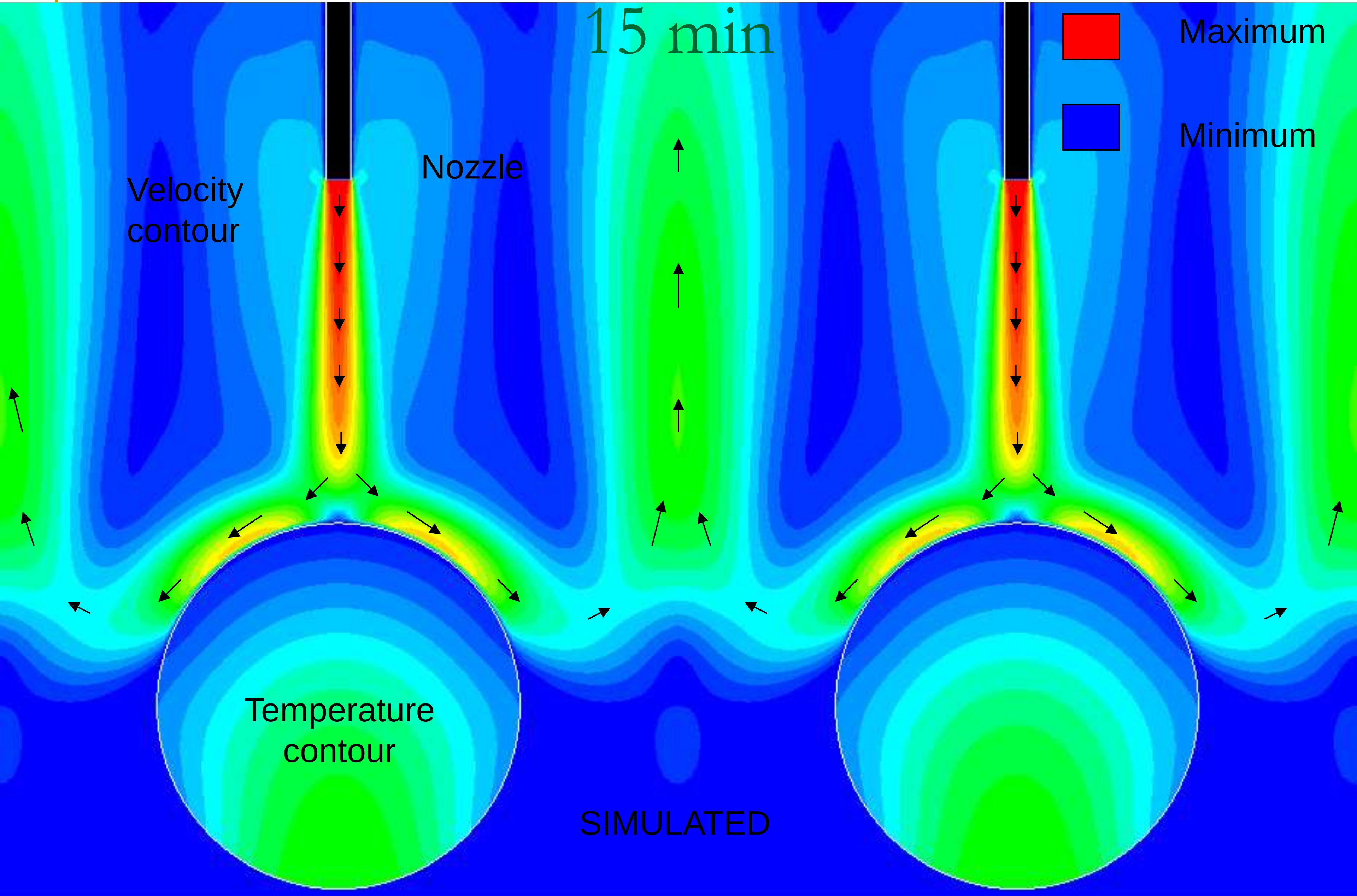
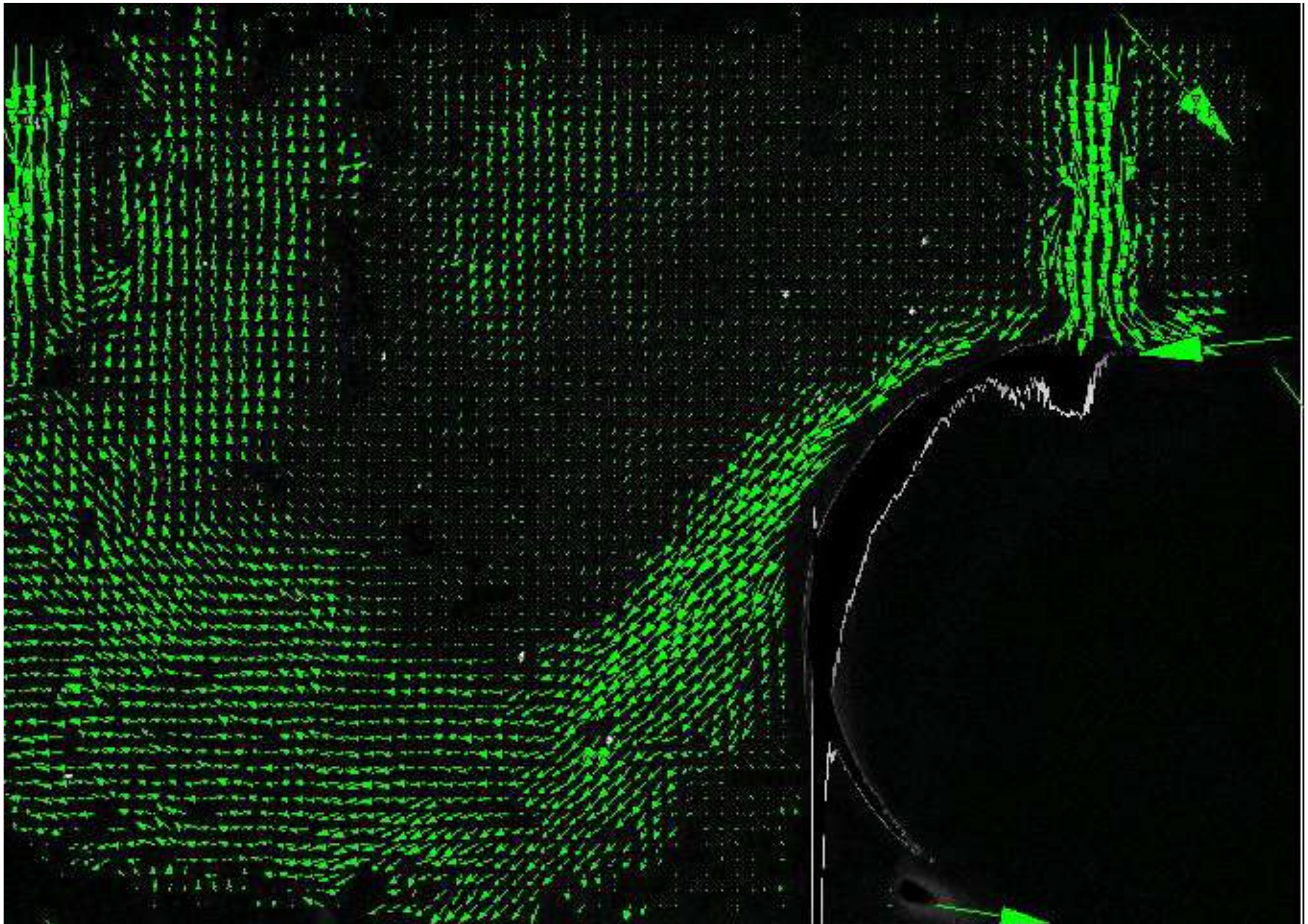
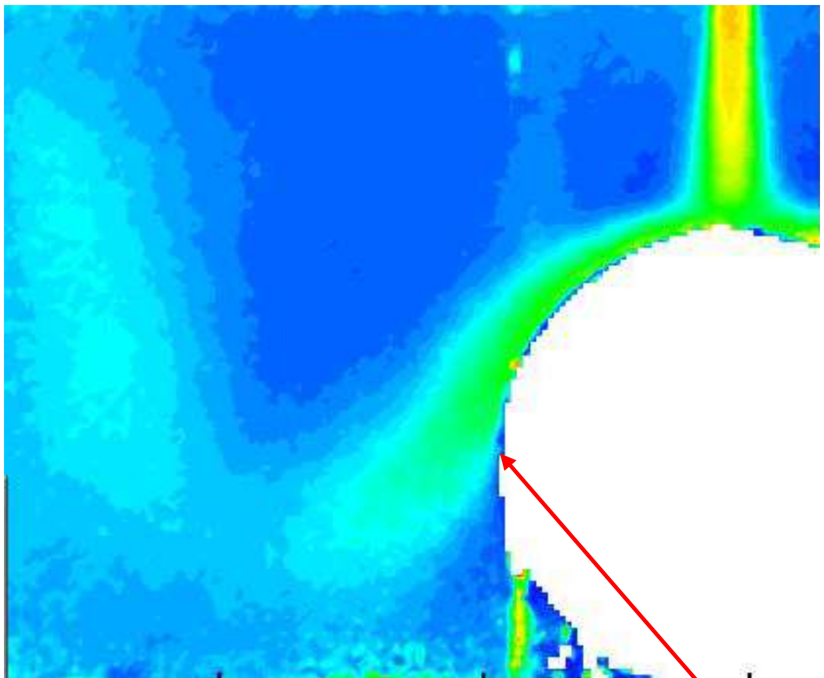
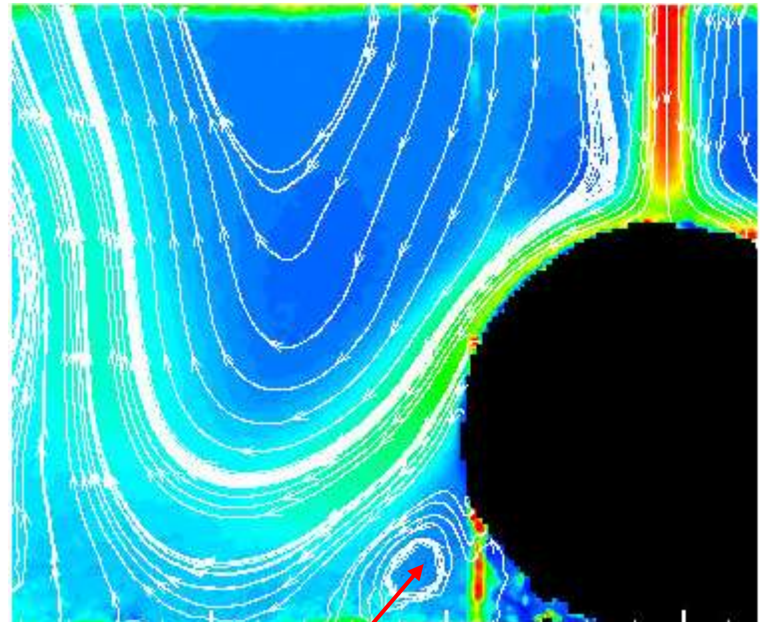


Velocity Vectors (From PIV)



Velocity Contours (From PIV)



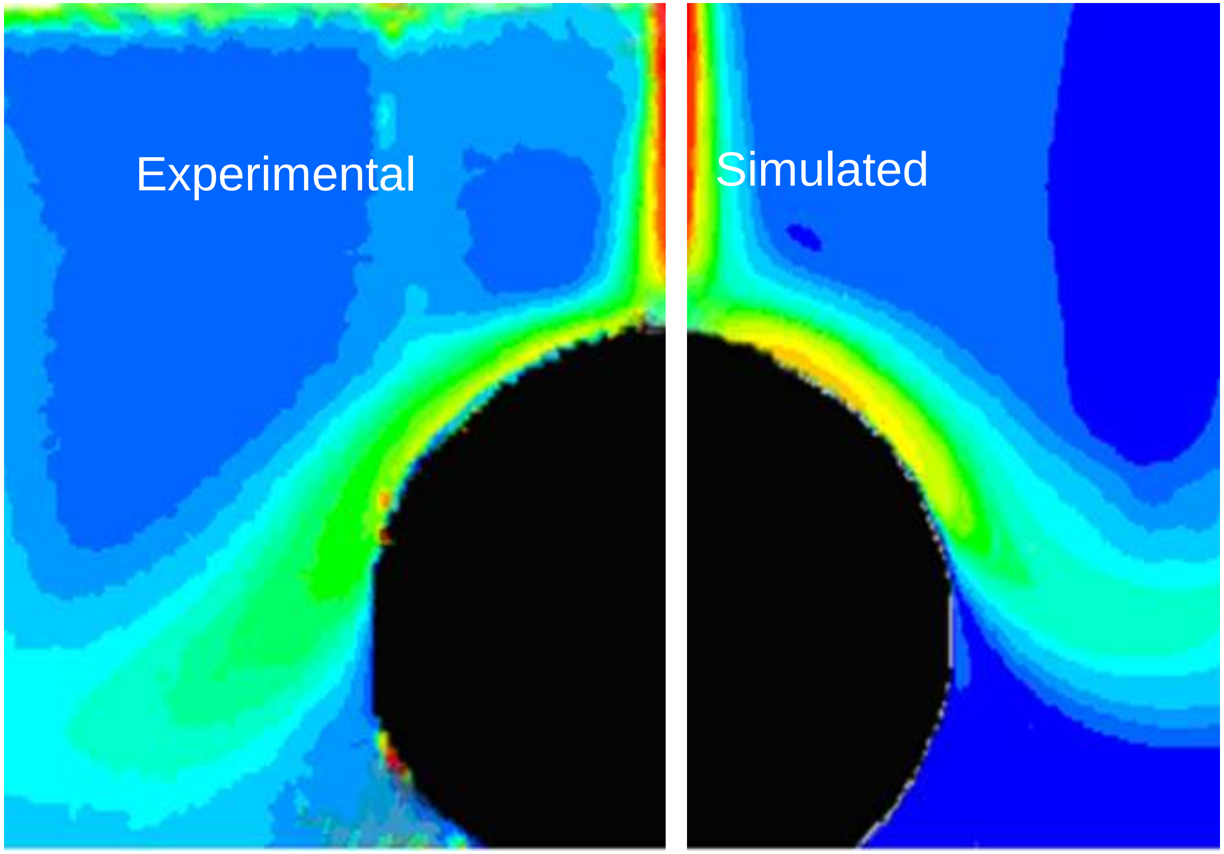


Flow separation

Flow recirculation

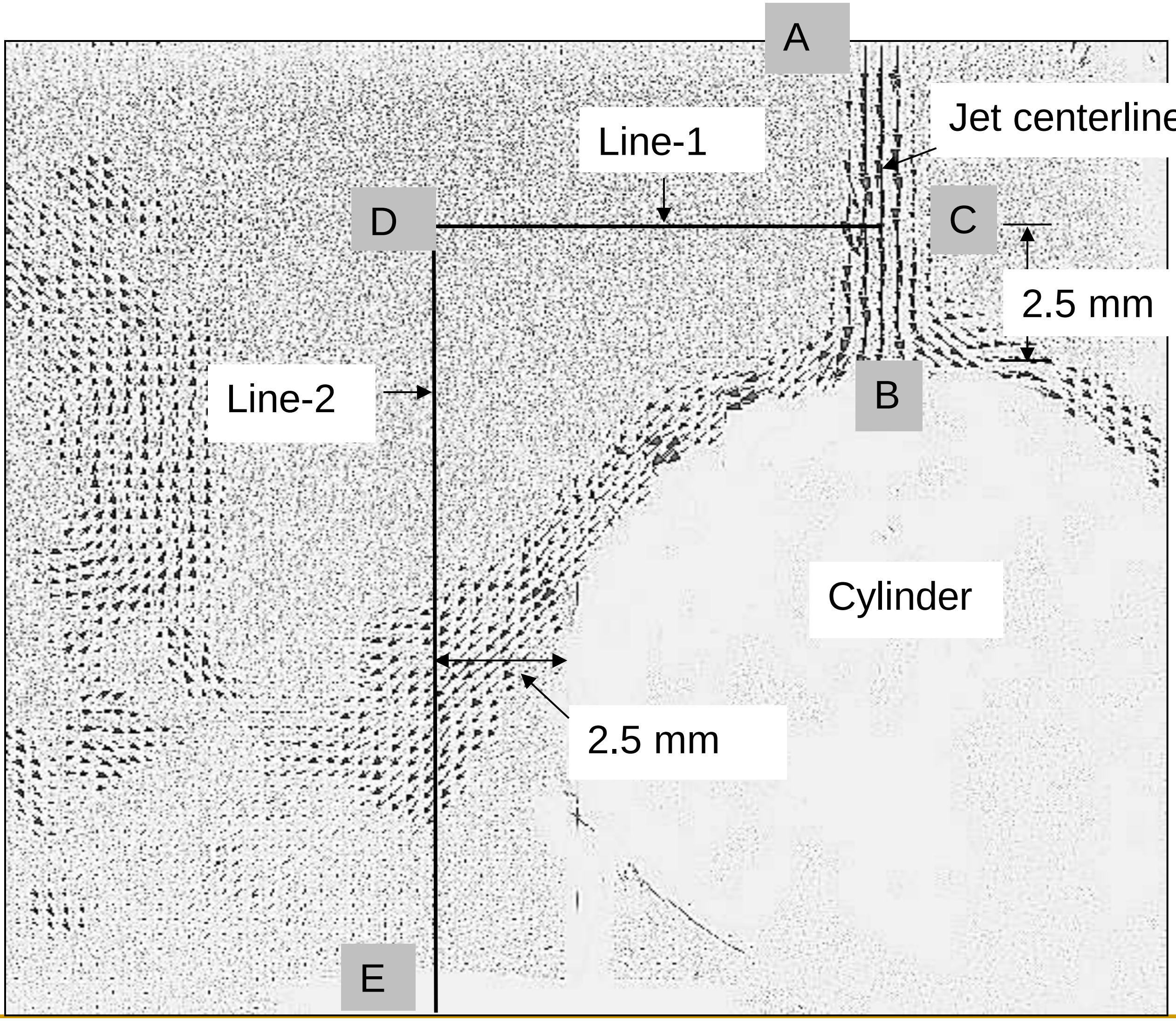
Velocity contours and streamlines (PIV)

Velocity Comparison (PIV vs. FLUENT)

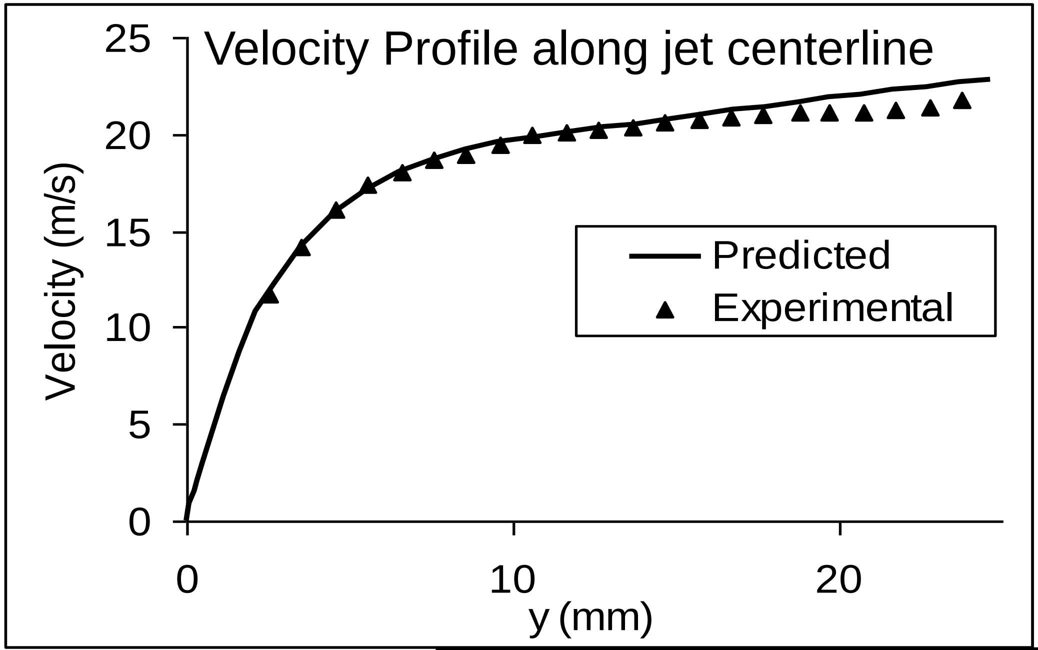


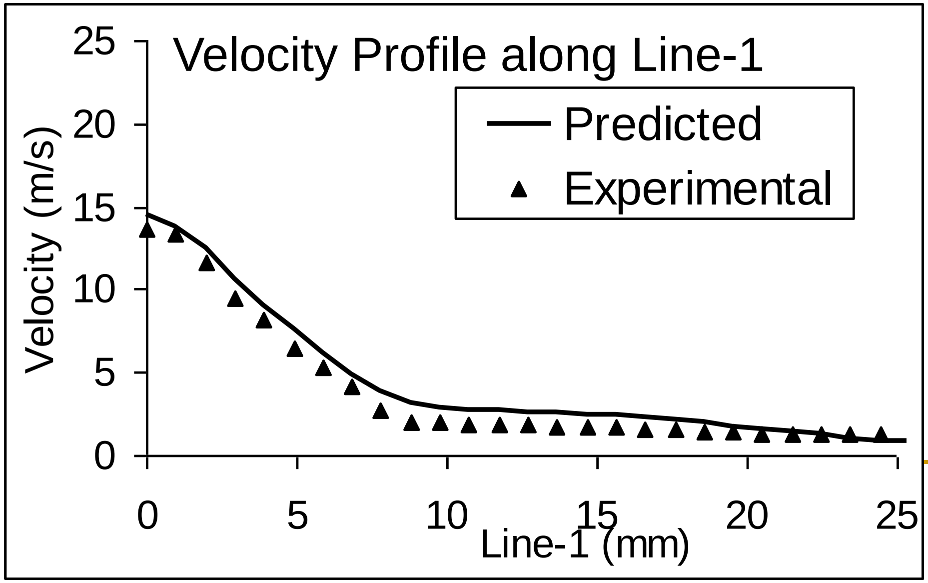
Velocity contours of simulated and PIV measured flow field

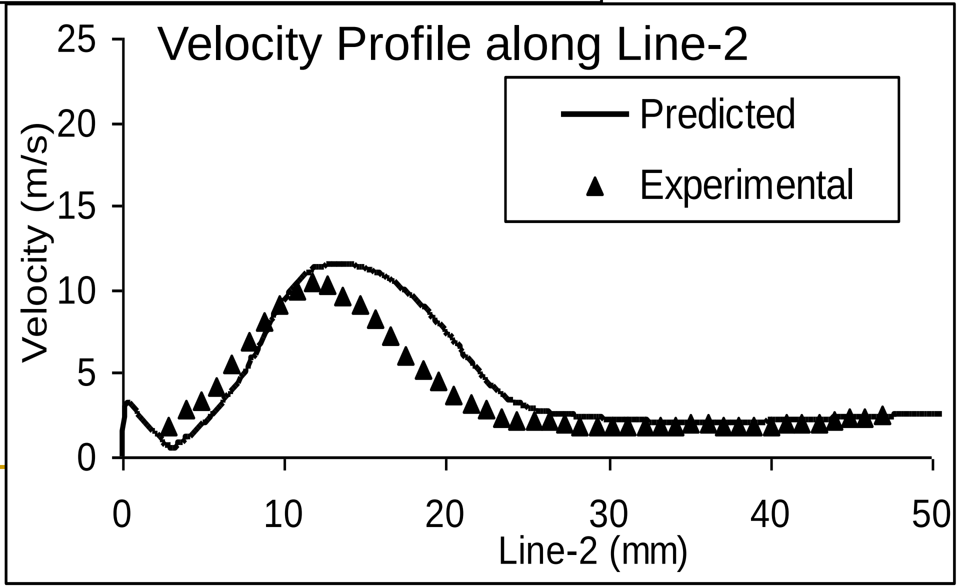
Velocity Comparison (PIV vs. FLUENT)



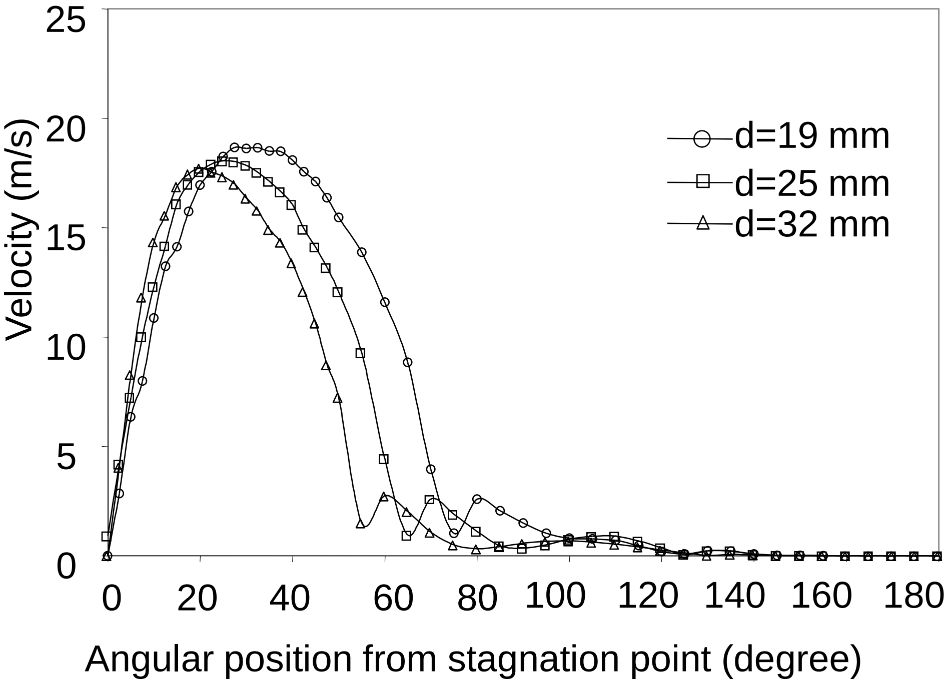
Flow field validation

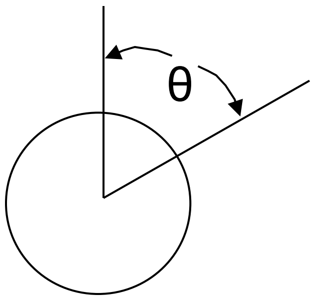


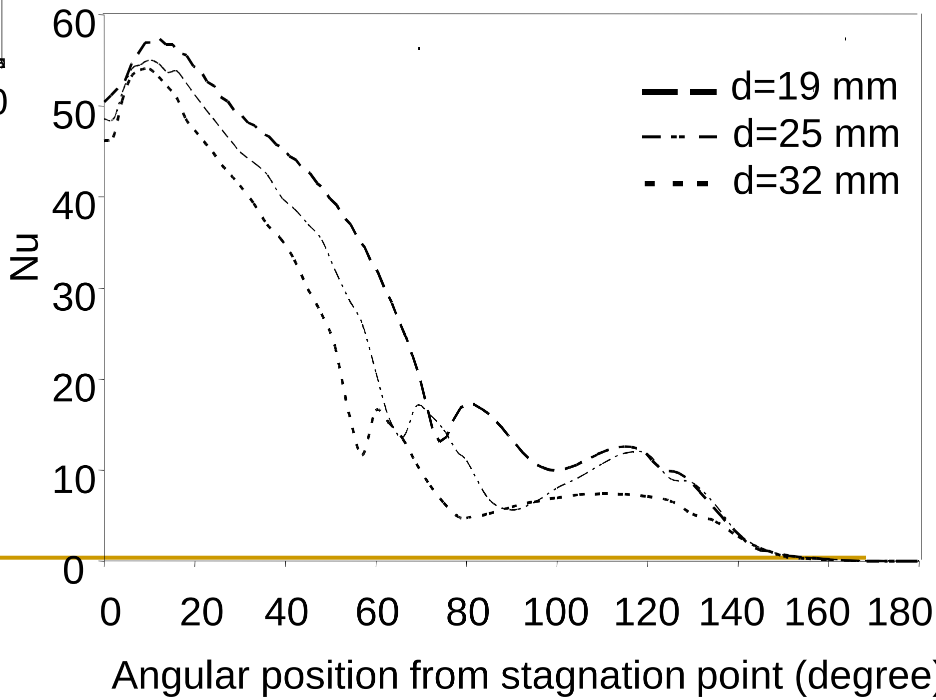




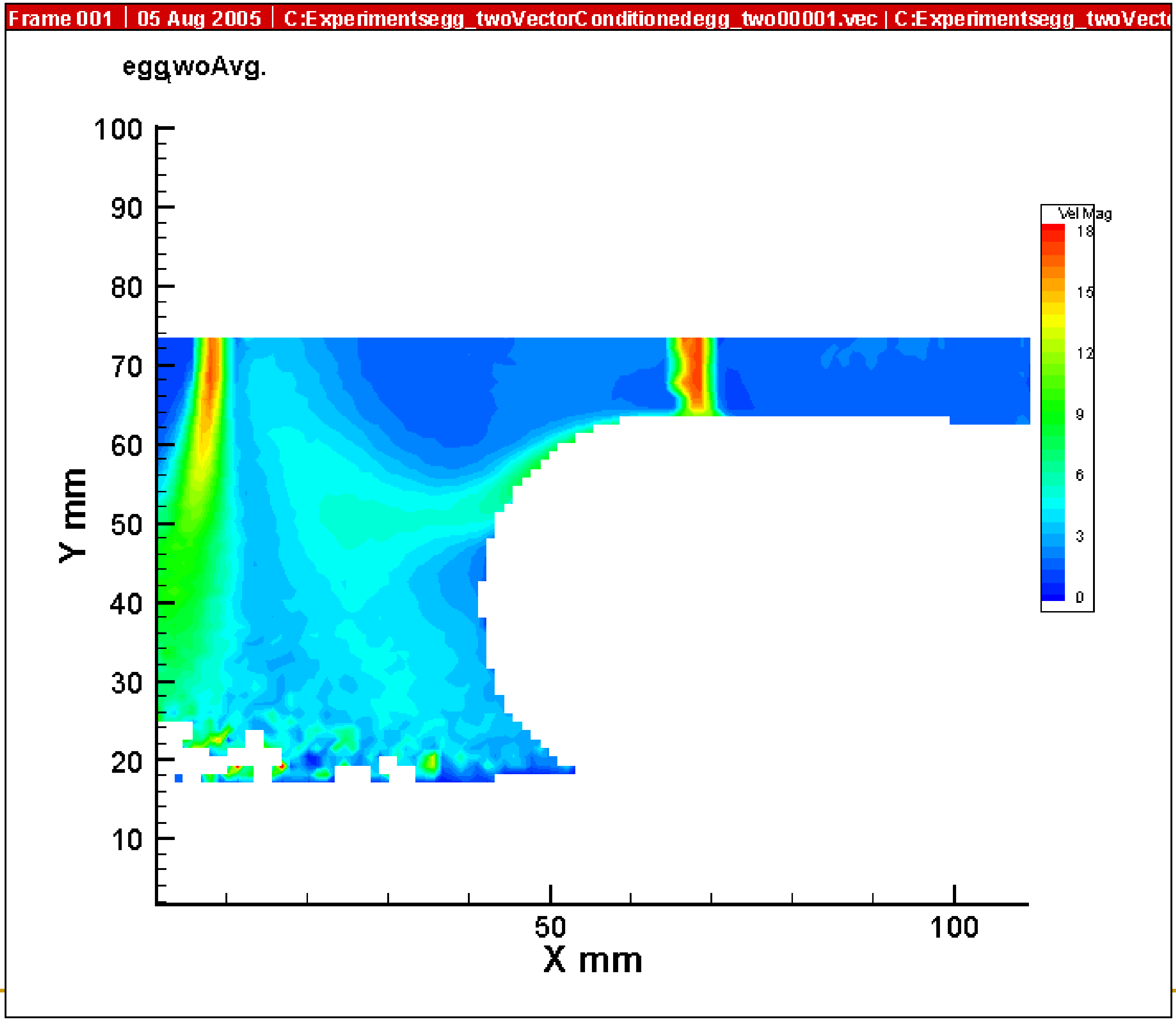
Effect of Surface Curvature of the Cylinder





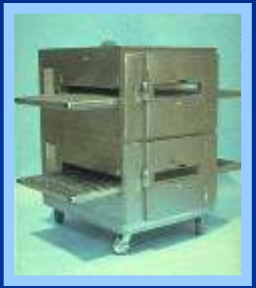


Cooling of Boiled Eggs



A Range of Platforms and Configurations

Food Processing
Stein (FMC)
APV Baker
FOODesign
Amana



Restaurants
Fujimak
Lincoln
Middleby
Carter Hoffmann

Non-traditional
Lincoln
Fujimak

Vending
KRh (Kaiser)
ACT

Residential
Thermador