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TITLE: The RCM1 - A Test Case. A First Attempt to Model a Supercritical Cryogenic Injection Using the CPS Code

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The RCM1_A test case

A first attempt to model a supercritical cryogenic injection using the CPS code

**2nd International Workshop on Rocket Combustion Modelling
Lampoldshausen March 25-27, 2001**

Presented by Laurent Lequette from Bertin Technologies

2nd RCM Workshop : RCM1_A test case

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The introduction

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- ❑ Bertin Technologies
 - ❑ technological services provider and consultancy
 - ❑ French private company
 - ❑ staff : 250 employees
- ❑ The SIMA team
 - ❑ working in Information Systems and Advanced Modelling
 - ❑ has been involved in CFD modelling for more than 15 years and has developed several CFD tools like CALIFE, THESEE and now CPS
- ❑ This work has been founded by CNES

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The introduction

The CPS code

- ☐ new generation CFD code
 - ☐ unstructured meshes (3D)
 - ☐ Roe and Toumi formulation for Euler fluxes
 - ☐ explicit and implicit schemes (for steady and for unsteady flows)
 - ☐ turbulence models (Jones-Launder, Coakley, RNG, subgrid, ...)
 - ☐ Eulerian two phases model
 - ☐ Lagrangian two phases model (LASVEGAS)
 - ☐ atomisation and coalescence
 - ☐ arbitrary time step
 - ☐ high volumic rates
 - ☐ Combustion models (Arrhenius, TECK, flame surface)
- ☐ developed by Bertin Technologies and SNPE Group together
 - ☐ benefits from earlier developments of both companies
- ☐ a commercial version is being launched
 - ☐ we are looking for pilot customers

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The objectives and the approach

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- ❑ The objectives
 - ❑ To have a first attempt to use CPS for supercritical flows
 - ❑ To retrieve guidelines for future developments of CPS
 - ❑ numerical point of view
 - ❑ physical models
- ❑ The approach
 - ❑ Several numerical strategies have been explored
 - ❑ two phases flow
 - ❑ single phase flow using Roe-Toumi fluxes and real gas law
 - ❑ single phase flow using a the ICED-ALE scheme and real gas law
 - ❑ implicit pressure treatment
 - ❑ transport of internal energy
 - ❑ Equation of state
 - ❑ large validity range Benedict-Weeb-Rubin (BWR) formulation
 - ❑ sound speed derived from this formulation

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The objectives and the approach

- The BWR equation of state for Nitrogen
 - 33 coefficients

$$\begin{aligned}
 P(T, \rho) = & \frac{\rho R T}{M} + \left(A1.T + A2.\sqrt{T} + A3 + \frac{A4}{T} + \frac{A5}{T^2} \right) \cdot \rho^2 + \left(A6.T + A7 + \frac{A8}{T} + \frac{A9}{T^2} \right) \cdot \rho^3 + \\
 & + \left(A10.T + A11 + \frac{A12}{T} \right) \cdot \rho^4 + A13 \cdot \rho^5 + \left(\frac{A14}{T} + \frac{A15}{T^2} \right) \cdot \rho^6 + \frac{A16}{T} \cdot \rho^7 + \left(\frac{A17}{T} + \frac{A18}{T^2} \right) \cdot \rho^8 + \\
 & + \frac{A19}{T^2} \cdot \rho^9 + \exp(-\gamma \cdot \rho^2) \left[\left(\frac{A20}{T^2} + \frac{A21}{T^3} \right) \cdot \rho^3 + \left(\frac{A22}{T^2} + \frac{A23}{T^4} \right) \cdot \rho^5 + \left(\frac{A24}{T^2} + \frac{A25}{T^3} \right) \cdot \rho^7 + \right. \\
 & \left. + \left(\frac{A26}{T^2} + \frac{A27}{T^4} \right) \cdot \rho^9 + \left(\frac{A28}{T^2} + \frac{A29}{T^3} \right) \cdot \rho^{11} + \left(\frac{A30}{T^2} + \frac{A31}{T^3} + \frac{A32}{T^4} \right) \cdot \rho^{13} \right]
 \end{aligned}$$

- The BWR enthalpy for Nitrogen

$$H(p, T) = H_0 + \int_{T_0}^T C_{p,0}(T) dT + \frac{p}{\rho(p, T)} - \frac{RT}{M} + \int_0^{\rho(p, T)} \left(\frac{p}{\rho^2} + \frac{T}{\rho^2} \left(\frac{\partial p(\rho, T)}{\partial T} \right)_{\rho} \right) d\rho$$

avec $H_0 = 0$

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The main results

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- ☐ The two phases approach could be interesting but is not mature enough in CPS for such a case
- ☐ As it is the Roe-Toumi scheme doesn't allow to use real gas properties
 - ☐ simplified laws may allow easier derivation
- ☐ The "old" ICED-ALE scheme works well for this case, without noticeable numerical difficulty, but :
 - ☐ the current API for real gas equation doesn't cover all aspects and has to be extended
 - ☐ the polynomial approach for C_p and C_v has to be extended to be more flexible
 - ☐ simplified boundary conditions had to be used in order to avoid perfect gas formulation
- ☐ For multispecies application the state of law for the mixing has to be built

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The numerical and the physical models

- ☐ Numerical models and parameters
 - ☐ Second order ICED-ALE scheme with implicit pressure treatment
 - ☐ CFL 5
 - ☐ conjugate gradient with ILU preconditioning
 - ☐ unsteady

- ☐ Physical models and parameters
 - ☐ BWR law of state
 - ☐ constant C_p and C_v $C_p = 1200. \text{ J.kg}^{-1}.\text{K}^{-1}$ $C_v = 800. \text{ J.kg}^{-1}.\text{K}^{-1}$
 - ☐ constant laminar viscosity
 - ☐ Jones-Launder (k, ϵ) turbulence model

- ☐ Mesh
 - ☐ 3230 elements
 - ☐ 154 elements in the axial direction

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The numerical and the physical models

- ☐ Inlet boundary conditions : fixed values
 - ☐ $P_s = 39.7 \cdot 10^5 \text{ Pa}$ $T_s = 126.9 \text{ K}$ $v = 0.769 \text{ m s}^{-1}$
 - ☐ $k = 0.0024 \text{ m}^2 \cdot \text{s}^{-2}$ $\omega = 10. \text{ s}^{-1}$
- ☐ Outlet boundary conditions : fixed pressure
 - ☐ $P_s = 39.7 \cdot 10^5 \text{ Pa}$ $T_s = 293. \text{ K}$ (for reentrant flow only) Free velocity
 - ☐ $k = 0.1 \text{ m}^2 \cdot \text{s}^{-2}$ $\omega = 40. \text{ s}^{-1}$
- ☐ Injector and pipe wall conditions
 - ☐ Adiabatic slip condition with friction
- ☐ Chamber back wall
 - ☐ Adiabatic Ordinary law of the wall
- ☐ Chamber lateral wall
 - ☐ Fixed temperature $T_w = 297 \text{ K}$ Ordinary law of the wall
- ☐ Initial conditions
 - ☐ downstream values with zero velocity

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The results

5

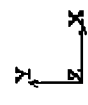
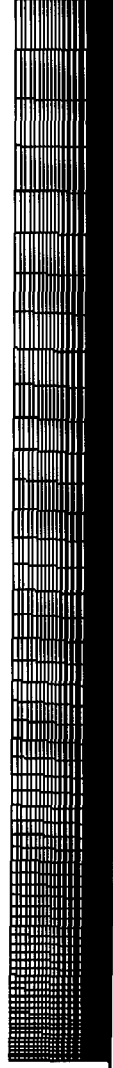
- ☐ The results correspond to
 - ☐ 50 000 time steps with laminar first order scheme
 - ☐ then 100 000 time steps with turbulent second order scheme
 - ☐ total CPU time 26 h on a Linux Xeon 350 MHz
- ☐ The results are converged in the jet spreading
 - ☐ at least down to 80 mm after injector outlet
- ☐ All the presented results are drawn with a radial to axial scale ratio of 5

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The results

5

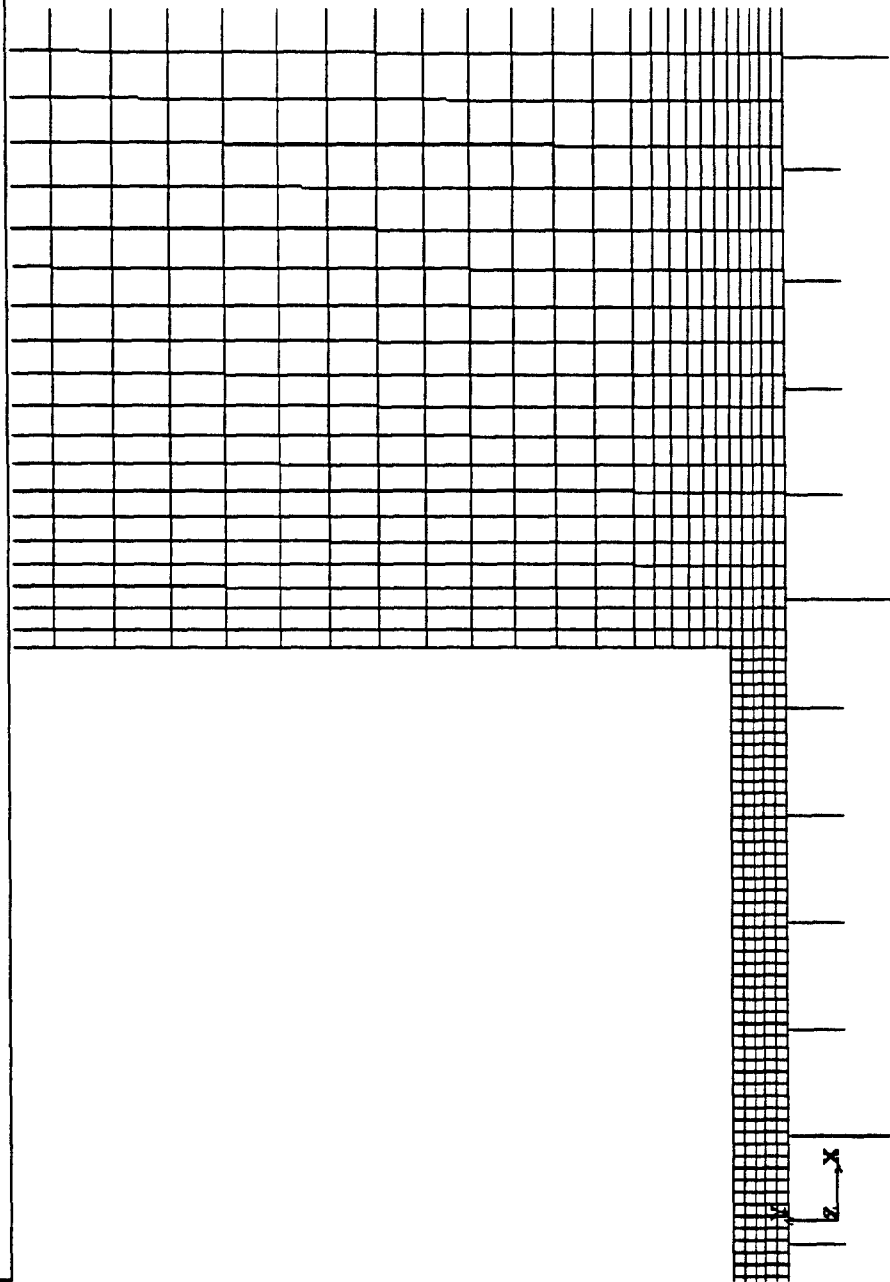
Mesh
RCM1
Overall view



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The results

Mesh
RCM1
Zoom

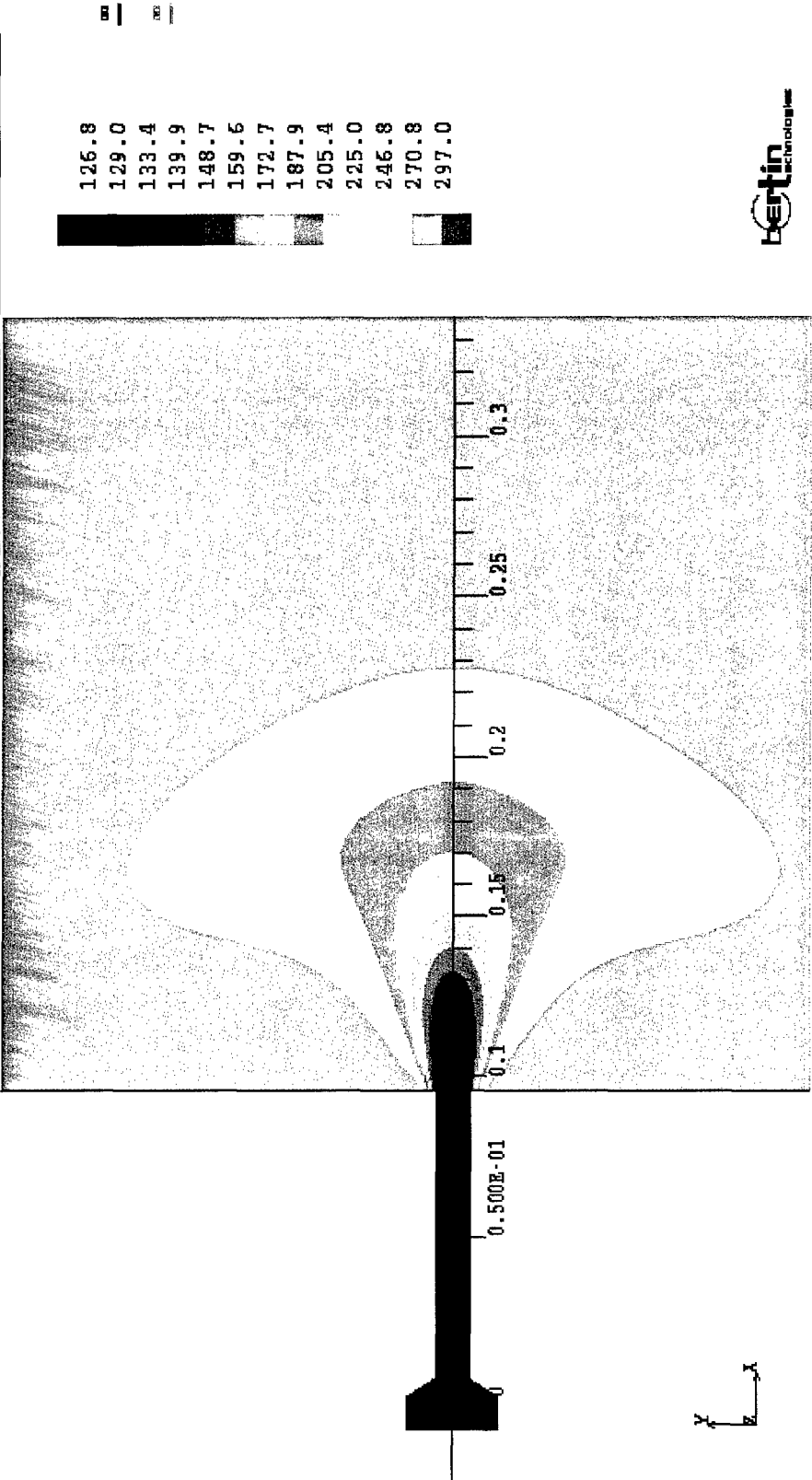


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The results

Temperature
case RCM1-A
LN2 at 126.9 K and 39.7 MPa

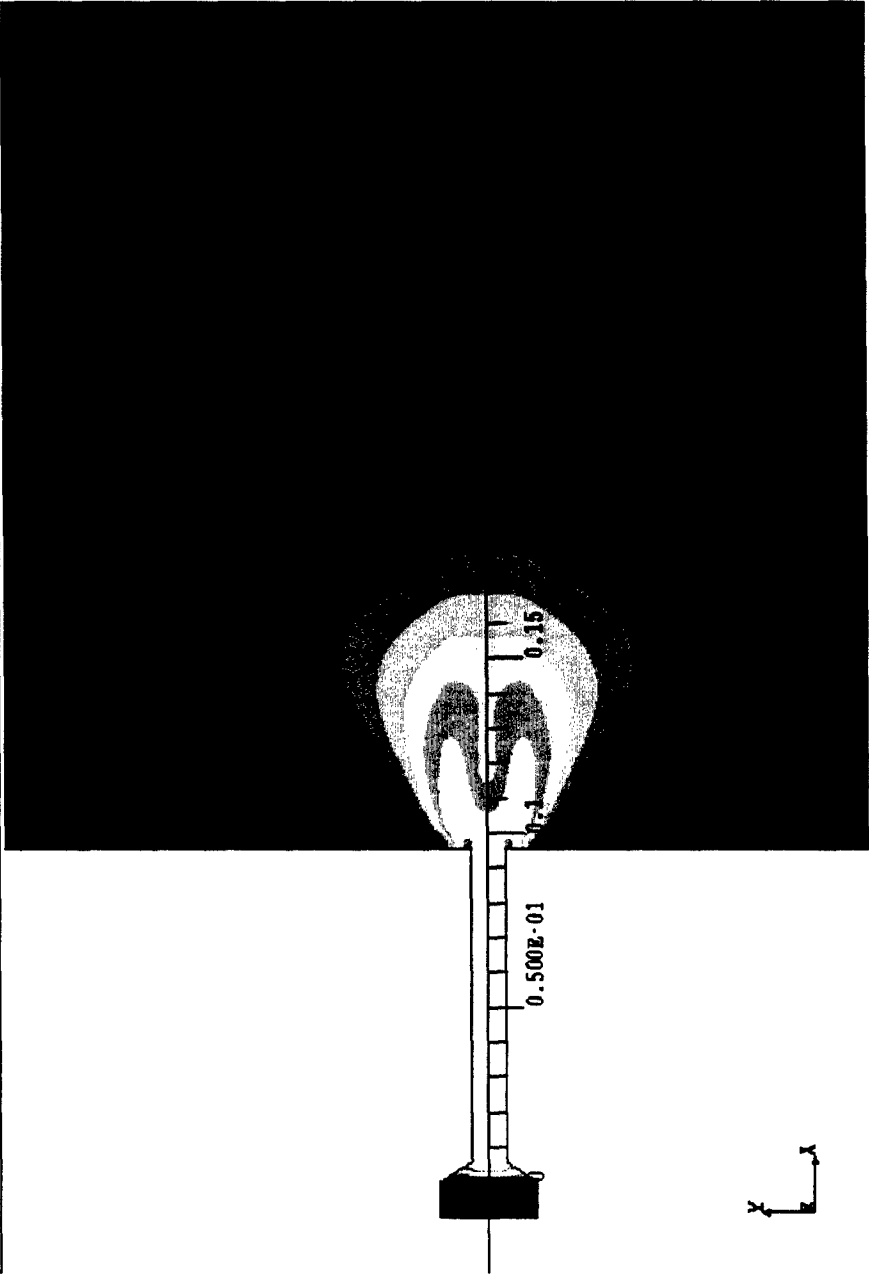
t : 0.20186
n : 100000
mini: 126.84
maxi: 297.00



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The results

Energie cinétique turbulente	t :	0.20186
case RCM1-A	n :	100000
LN2 at 126.9 K and 39.7 MPa	mini :	2.09170E-03
	maxi :	4.6508



0.2092E-02
0.1461E-01
0.3340E-01
0.6157E-01
0.1038
0.1672
0.2623
0.4049
0.6189
0.9398
1.421
2.143
3.226

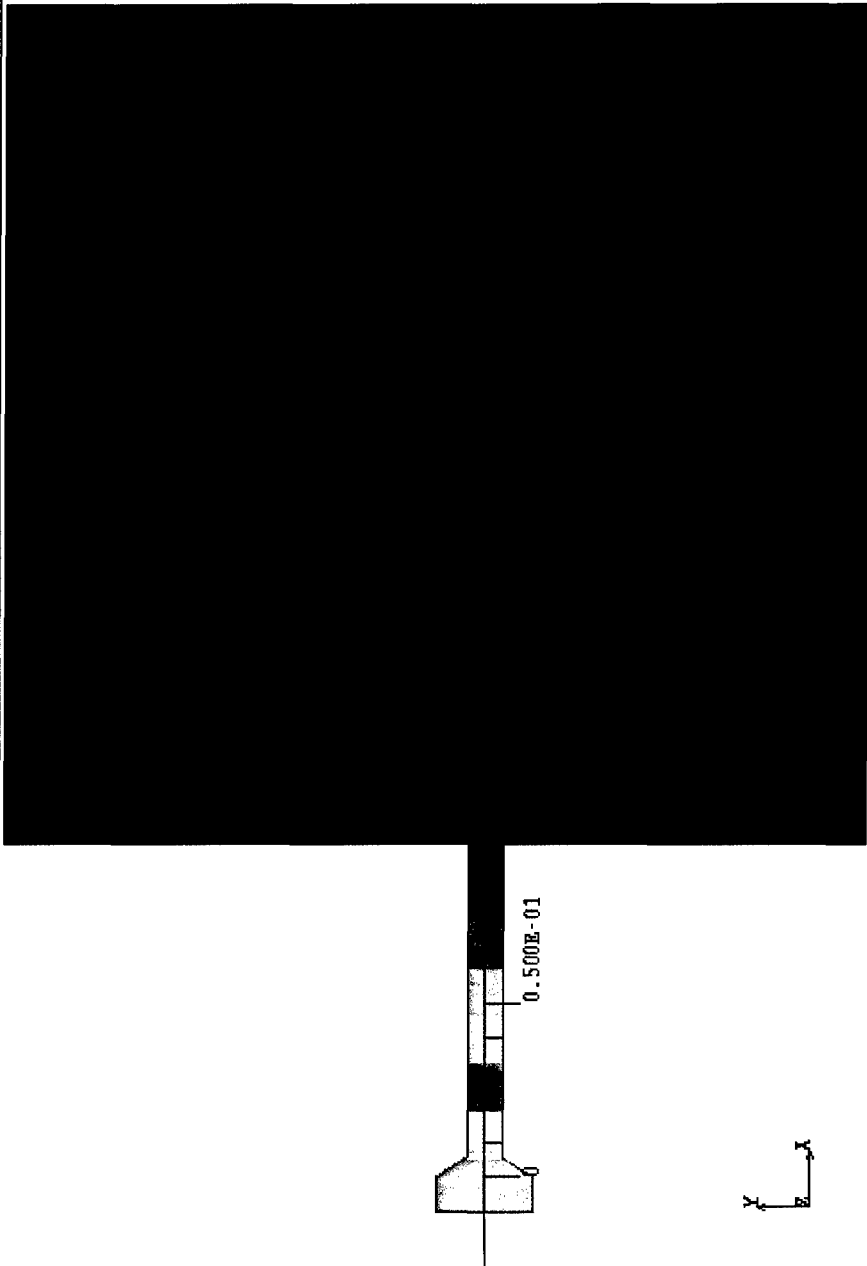


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The results

Pression
case RCM1-A
LN2 at 126.9 K and 39.7 MPa

L : 0.20186
n : 100000
mini: 3.96131E+06
maxi: 4.01469E+06

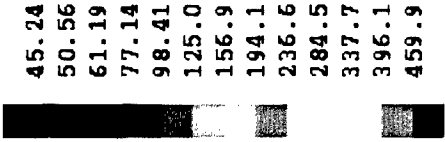
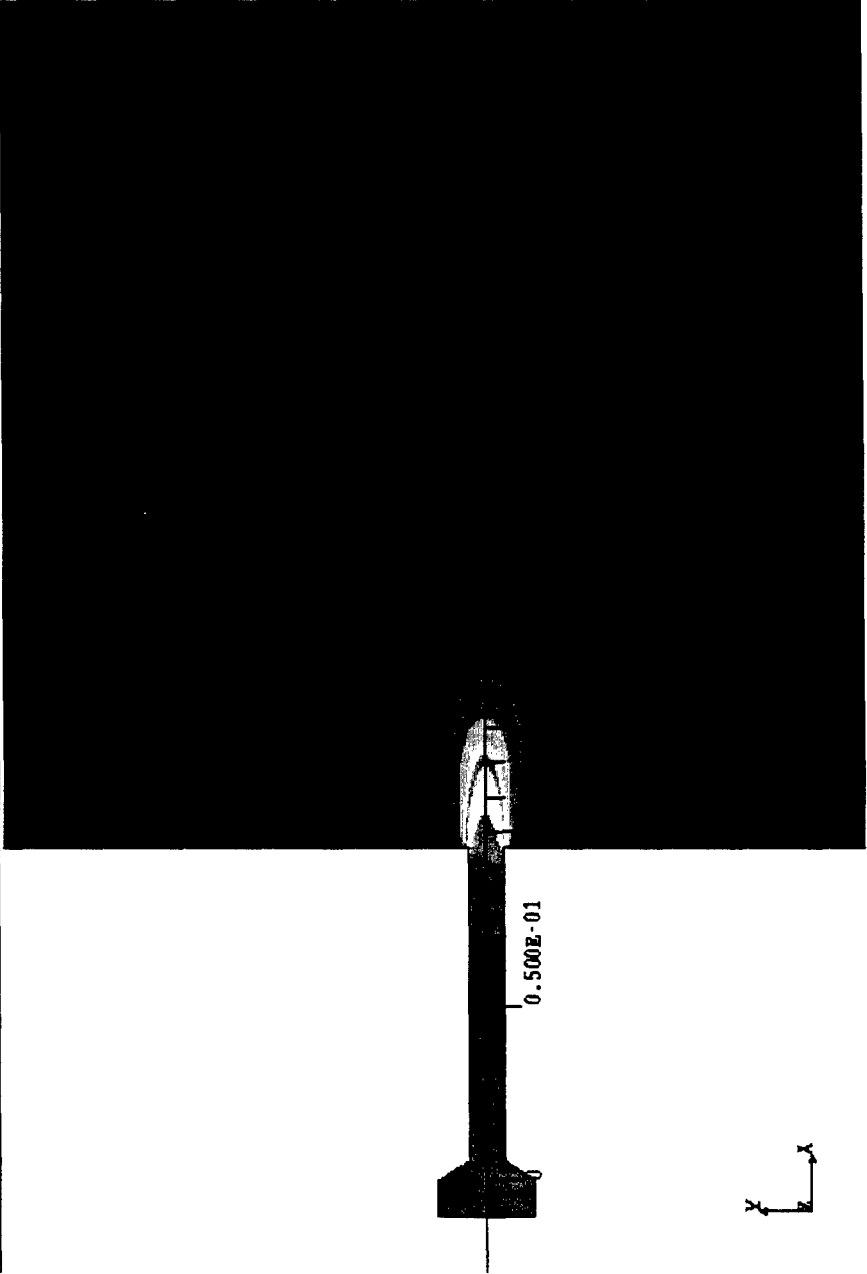


0.3961E+07
0.3966E+07
0.3970E+07
0.3975E+07
0.3979E+07
0.3984E+07
0.3988E+07
0.3992E+07
0.3997E+07
0.4001E+07
0.4006E+07
0.4010E+07
0.4015E+07



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The results

Masse volumique	t :	0.20186
case RCM1-A	n :	100000
LN2 at 126.9 K and 39.7 MPa	mini :	45.244
	maxi :	459.95

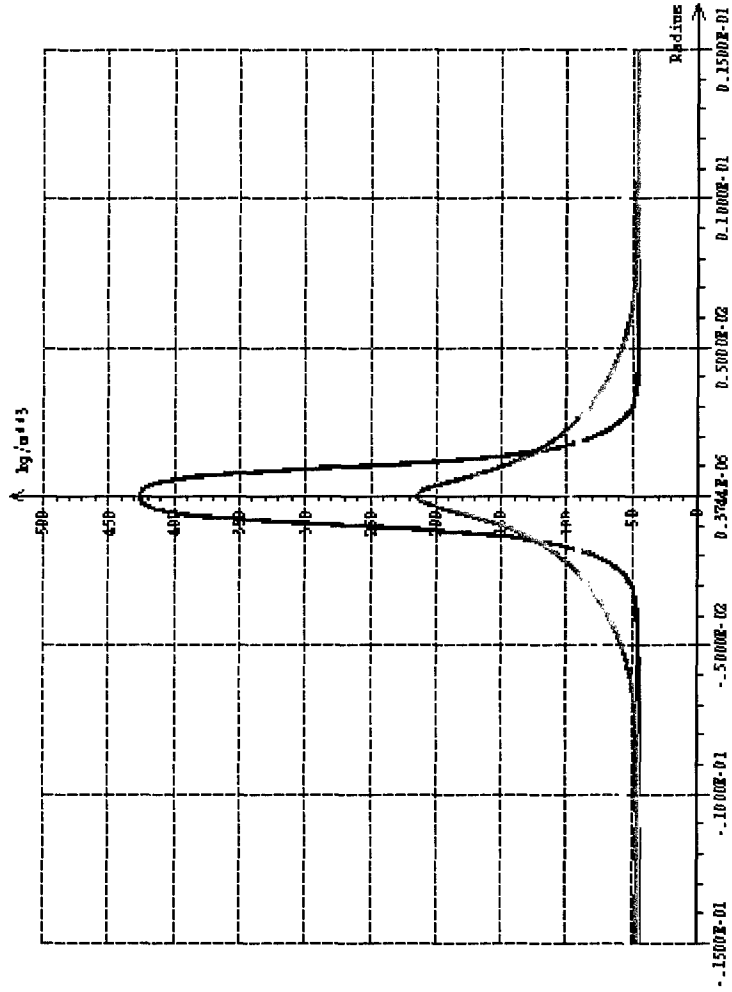


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The results

5

Masse volumique	t :	0.20186
case RCM1-A	n :	100000
LN2 at 126.9 K and 39.7 MPa	mini :	45.244
	maxi :	459.95



$x = 5.00$

$x = 25.00$

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The conclusion

- ☐ This preliminary attempt to model a supercritical cryogenic injection with a general purpose code has shown that it is feasible
- ☐ Sophisticated thermodynamic laws :
 - ☐ can be taken into account with simple numerical schemes
 - ☐ require to adapt many features including boundary conditions
 - ☐ cannot yet be taken into account easily for ordinary users
 - ☐ induce a large CPU cost
- ☐ Further developments must be done to be able to use Roe-Toumi fluxes
- ☐ Simplified laws would help to implicit these schemes