Hands on computer session:
2. Compressible flow through a converging diverging nozzle
[Time: 1 h]

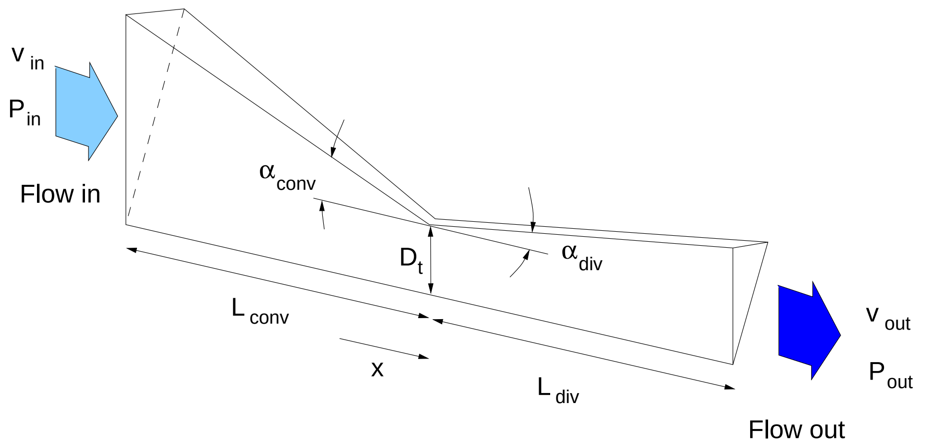
Objects

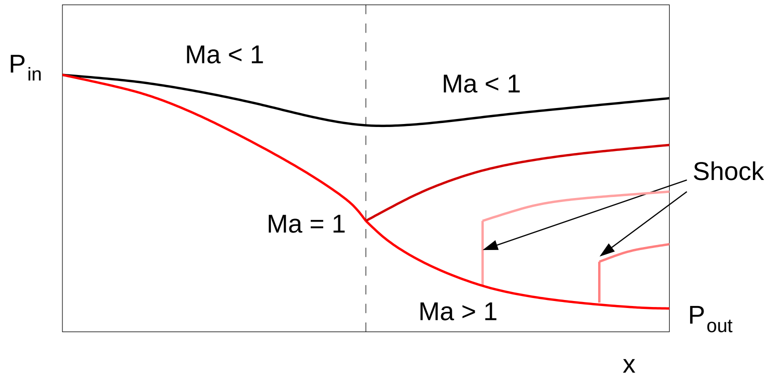
- choice of computational domain and definition of optimal boundary conditions
- techniques to obtain a smooth meshing of a "complex" domain, "a posteriori" checks for accuracy against theory, tools for adaptive grid refinement;
- identification of reference data, calculation of global quantities;
- balancing accuracy vs computational time and resources;
- use of MACRO for problem set up and resolution, use of INTERNAL BOUNDARY for post-processing;

Physical problem

Flow of compressible fluid accelerating in the convergent and decelerating in the divergent part of the nozzle:

- different flow regimes are possible depending on flow rate (or inlet/outlet pressure difference) and geometry of the nozzle (subsonic/sonic/supersonic flow);
- nozzle geometry controls efficient recovery of pressure energy;
- a shock wave may form in the divergent.





Data

Throat diameter	$D_t = 30\ mm$
Ratio of exit area (Ae) to the throat area (At)	$Ae/At = 4$
Convergent lenght	$L_{conv} = 40\ mm$
Divergent lenght	$L_{div} = 160\ mm$
Inlet Pressure	$P = 600\ kPa$
Inlet Temperature	$T = 293\ K$
Outlet Pressure	$P = 600\ kPa \div 0\ kPa$

Worksheet

Mesh generation	• evaluate number of required grid nodes (wall layer and streamwise resolution), with specific attention to the divergentpart of the nozzle (flow detachment from the wall, possible shock region) → use patches to generate blocks of cells
Boundary conditions	→ use cyclic B.C. to set up a bidimensional simulation → use Pressure at inlet and Pressure at outlet → use INTERNAL boundary conditions to monitor flow rate at throat → use a TABLE to decrease the pressure at outlet
Initial conditions	• outlet pressure equal to inlet pressure
Solution method	• transient simulation, with variation of outlet B.C. → choice of relaxation factor → choice of differencing scheme • comparison with steady state simulation (at each regime)
Results	→ use of SENSOR to plot pressure and Mach variation along the nozzle axis → identification of shock region, adaptive grid refinement to capture the sharp pressure gradient at the shock line → use of MACRO and fortran coding to evaluate thrust at nozzle exit

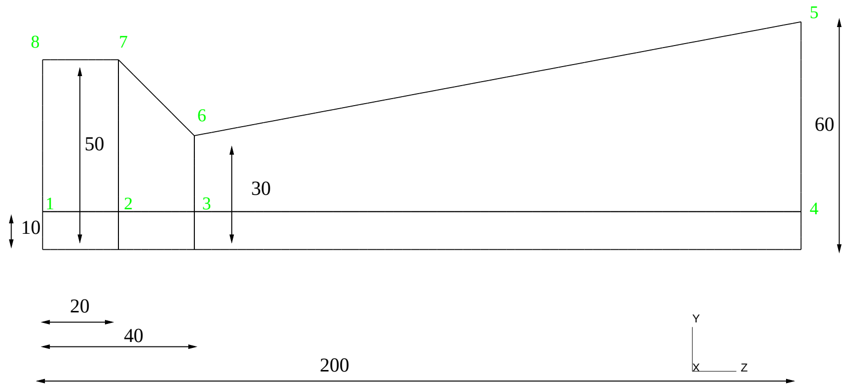
References

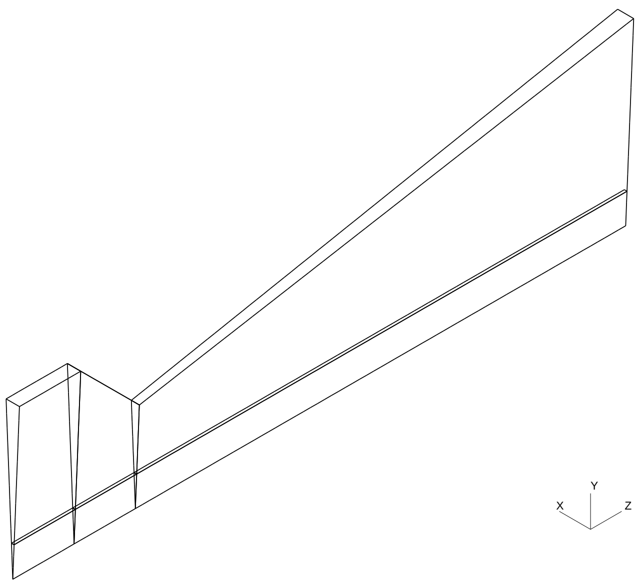
Hadjadj, A., Nebbache, A., Vuillamy, D. and Vandromme, D. (1997), "Numerical simulation of flow separation in rocket nozzle", *Mechanics research Communications*, **24**, 269-276.

Hussaini, M. M., and Korte J. J., (1996), "Investigation of low Reynolds number rocket nozzle design using PNS-based optimization procedure", *NASA Technical Memorandum 110295.*

http:// www.engapplets.vt.edu/fluids/CDnozzle

Geometry





MACROS

```
!****************
! Geometry.MAC *
!****************
!——————————————
!*** generation of points and splines
!——————————————
csys 2
v 1 10 92.5 0
v 2 10 92.5 20
v 3 10 92.5 40
v 4 10 92.5 200
v 5 60 92.5 200
v 6 30 92.5 40
v 7 50 92.5 20
v 8 50 92.5 0
!———————————————-
!*** generation of patches and 2D geometry
!———————————————-
ctab 4 shell 2
patch 1 2 7 8 10 10
ctab 5 shell 3
patch 2 3 6 7 10 10
patch 3 4 5 6 70 10
vmer all
c
vcomp all
y
cset all
cplo
!——————————————————————-
!*** extrusion of 2D geometry and creation of 3D mesh
!——————————————————————-
csys 2
vcextrude,1,mini,cset,,,local,,-5,,both
cset news fluid
view,-1,1,1
cset news shell
cdel cset
ccomp all
y
cset all
ctype 1
cmod cset
get coff mxce
cflip,1,coff,1,right
vc3d 0 10 3 87.5 92.5 1 0 20 10
vc3d 0 10 3 87.5 92.5 1 20 40 10
vc3d 0 10 3 87.5 92.5 1 40 200 70
cset all
vmer all
c
```

```
vcomp all
y
cset all
view,-1,0,0
cplo
!————————
!*** save the model
!————————
save exe2.mdl



!******************
! scalar-axis.MAC *
!******************
!——————————————————
!*** load transient solution
!——————————————————
trload,exe2.pstt,nomvgr,,c
————————————
—*** loop definition
!————————————
!*define
stor next
getv,T
greset
y
sens dele all
cset all
gpost,points,nomap,50,1,0,0.1,0,0,0.1,200
frame,1,xreg,init,2
frame,1,xrange,0,200
frame,1,xtitle,4.3,1.5
DISTANCE
frame,1,yreg,init,9
frame,1,yrange,200,300
frame,1,ytitle,0.5,5.5
T
!scdu,gif,frm
gdraw,1
!scdu,off
!*END
!*loop 1 70



!****************
! animation.MAC *
!****************
!————————————
!*** load transient solution
!————————————
trload,exe2.pstt,nomvgr,,c
cset news fluid
```

```
cplo
csca,20,user,0,4,,
!csca,20,auto
!—————————–
!*** loop definition
!—————————–
DEFI
STOR NEXT
!GETC all
oper,getc,t,1,absolute
oper,smul,402.768,1,1
oper,sqrt,1,2
oper,getc,sw,3
oper,divi,3,2,4
CAVER CSET
PLTB ON
REPLOT
PLTB OFF
END
LOOP 1 101


!********************
! film-2windows.MAC *
!********************
!———————————–
!*** load transient solution
!———————————–
TRLOAD,,
N
window,default
window,divi,2,1
POPT,CONT
PLTY EHID
CSET NEWS FLUID
TRINTERPOLATE,ON,CAVER CSET
!—————————–
!*** loop definition
!—————————–
SET FRM 1001 1
DEFI NOEX
STOR NEXT
window,activate,1,1
pldi,off,all
oper,getc,t,1,absolute
oper,smul,402.768,1,1
oper,sqrt,1,2
oper,getc,sw,3
oper,divi,3,2,4
caver,cset
CSCA,20,user,0,4,,
pldi,on,scale
PLDI,ON,TITLE
```

```
TITLE
NOZZLE - Mach Field and Axis Pressure
CPLO
window,activate,next
getv,pstat,relative
greset
y
sens dele all
csys 1
gpost,points,nomap,50,1,0,1,0,0,1,200
frame,1,xreg,init,2
frame,1,xrange,0,200
frame,1,xtick,50,0,integer,
frame,1,yreg,init,9
frame,1,yrange,-600000,0
frame,1,ytick,0,1000,real,right
frame,1,ytitle,0.5,3.5
PRESSURE
grdisp,1,off,yscale
SCDU,GIF,FRM
gdraw,1
SCDU,OFF
END
LOOP,1,300,1
```