

Sample Problem for Compressible Flow about a Thrust Deflector

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A. Problem Description

To illustrate how the FLOW-3D program may be used to model compressible, subsonic flow we have performed a calculation of nozzle flow impinging upon thrust deflector plates.

The basic geometric arrangement is illustrated in Fig. 1. At the left side of the x-z cross section there are two regions of specified inlet flow. Flow 1 enters the computational region within a circular radius of 13.19" (33.5 cm). Flow 2 enters in the annular region extending from 13.19" to 21.16" (53.75 cm). Outside of this annulus a constant atmospheric pressure is used as a boundary condition. A cylindrical baffle surrounds the outer edge of the Flow 2 annulus and extends into the flow region 41.6" (105.66 cm). The thrust deflector is a portion of a cylinder whose axis has been tilted 9° with respect to the x-axis. In the x-z cross section of Fig. 1, the right most edge of the cylinder is depicted by the slanted line at the right side of the flow region. This cylinder has a radius of 21.16" (53.75 cm) and is chopped off above $x = 41.1$ " (104.39 cm). The deflector is also limited to ~~7~~ greater than 46" (116.84 cm). Thus, there is a 4.4" (11.18 cm) gap between the end of the baffle and the beginning edge of the deflector. The baffle and deflector limits are indicated by dashed lines in Fig. 1.

This problem has symmetry across the $x=0$ and $y=0$ planes, so that only one quadrant of the problem was modeled. All boundaries of the flow region were treated as constant pressure boundaries, except for the inlet flow inside the baffle at $z=0$.

The computational mesh layout used for this three-dimensional problem is shown in Fig. 2. The mesh consists of $15 \times 12 \times 13 = 2340$ interior cells (or 3570 cells including boundaries). Because a Cartesian mesh was used, the cylindrical baffle must be approximated by a stepped boundary. That is, a baffle is a wall of zero thickness and can only be defined at cell faces. In Fig. 3 the annular region for Flow 2 has been shaded in so that the baffle is defined by the outer surface of this region. The inner surface indicates the boundary of the Flow 1 inlet region.

Inlet Flow 1 is air at a temperature of 894°F (752°K), has a

pressure of 20.52 psi (1.415×10^6 dynes/cm²) and has a specified velocity of 560 ft/s (1.707×10^4 cm/s). Flow 2 is air at a temperature of 144°F (335°K), has a pressure of 22.19 psi (1.53×10^6 dynes/cm²) and has a specified velocity of 495 ft/s (1.51×10^4 cm/s).

The Reynolds number for Flow 1 is about 4×10^6 , which indicates highly turbulent flow. To model this turbulence we assumed the effective turbulent Reynolds number is 100, a value typical of many kinds of flows. Thus, the coefficient of viscosity was selected as $\mu = 7.5$, which corresponds to a turbulent Reynolds number of 100 based on the incoming velocity and diameter of Flow 1.

A first attempt to solve this problem was made using a cylindrical coordinate system so that the baffle could be modeled as a true cylinder. However, convergence of the mesh lines at the axis of symmetry led to small cell sizes in the azimuthal direction that held the time step to an unacceptably small level. In any case, we expect the baffle used in the Cartesian mesh to be a good approximation because the incoming flow is turbulent and will quickly smooth any perturbations arising from the stepped baffle geometry.

B. Computational Results

At time zero all fluid in the calculational region is at rest. Figure 4 shows the velocities and temperature contours at an early time (0.003 s) in the x-z symmetry plane. Since the acoustic transit time between the inlet and the deflector is about 0.004 s, no disturbance has reached the deflector at this time.

As time progresses, the flow will eventually reach a steady state. Because this is only a sample calculation, we elected to terminate it after 0.0092 s, or somewhat short of steady state conditions. Nevertheless, the overall flow and asymptotic trends are clearly evident by this time.

Figure 5 shows the x-z symmetry plane velocities and temperatures at 0.0092 s, while Fig. 6 shows the corresponding plots in the y-z plane of symmetry. It is evident from these plots that a considerable amount of turbulent mixing has occurred downstream of the inlet and smoothed the large temperature difference initially present between Flows 1 and 2. The evolution of this mixing as the flow develops can be seen from a comparison of the temperature contours contained in Fig. 7. This composite plot shows the contours in the x-y plane at the end of the cylindrical baffle. Reading from left to right and top to bottom the individual plots correspond to the times 3, 5.4, 6.8,

and 9.2 ms.

The flow structure on the surface of the thrust deflector is difficult to show because of its curvature. However, a good idea of what is happening there can be gleaned from Fig. 8. The left plot shows a perspective of the velocities in the $z = 62.2$ " (158 cm) plane. The right plot is in the $z = 66.5$ " (169 cm) plane. Note that the point marked "z" is furthest from the eye. Blank regions in these plots are where the curved thrust deflector intersects the plane containing the velocity vectors. Clearly, the flow inside the deflector is being channeled in the x-direction (i.e., parallel to the axis of the cylindrical deflector). Outside of the deflector the flow is rapidly expanding into the surrounding air.

A somewhat better idea of the flow orientation is provided in the stereo pair contained in Fig. 9. The stereo view clearly shows that the flow outside the deflector is directed away from the eye, while the flow inside has a small component toward the eye because of the forward tilt of the deflector. In retrospect, the eye locations selected for the stereo plots were not ideal. However, a new postprocessor for FLOW-3D (that was not available at the time this calculation was run) allows the user to redo such plots from any angle, eye separation, etc. (The new graphics package also has the label positioning corrected so that it will not overwrite the plot!).

It is worthwhile to note that the maximum velocity in the Fig. 8 plots indicates a local Mach number in excess of 0.7. This is significantly higher than the Mach number of either inlet flow (0.31 and 0.41). Although the flow remains subsonic, the occurrence of Mach numbers in this range indicates the need for the full compressibility model used in FLOW-3D. The code does have an optional limited compressibility model, but this is for acoustic effects only and is not recommended for flows at Mach numbers above 0.1.

Pressure distributions in the $z = 62.2$ " and $z = 66.5$ " planes are shown in Fig. 10. The lower half of each plot corresponds to the region within the deflector. A strong gradient is observed between the high near the $x=0$ surface and the low near the top (large x) end of the deflector. The lowest pressure in these plots is outside the deflector, which explains why there are no contours plotted between the indicated low (L) and high (H) points.

FLOW-3D has provisions for internally computing forces and moments on obstacles located within the mesh. Using this feature, the force on the front face of the deflector was computed, Fig. 11. At time 0.0 the force is 6.39 tons, which is

entirely due to the initial pressure of one atmosphere. The 10 ton peak in force at 5 ms may be slightly in error because the force sampling frequency was rather coarse during the first 6 ms of the transient. It appears that the steady state thrust (i.e., force minus 6.39 tons) could be slightly greater than 1.11 tons. A simple hand calculation indicates that this is quite reasonable. The average dynamic pressure ($\rho u^2/2$) of the inlet is about 2.0 psi, which would yield a net thrust of order 0.86 tons. However, the deflection of the flow back towards the inlet should increase the thrust above this estimate somewhat. If the flow were completely reversed, the thrust would be 1.72 tons. We expect, therefore, a steady state thrust somewhere between 0.86 and 1.72 tons, but weighted more toward the lower end of this range because the backward deflection is small.

It is interesting to note that the peak thrust (3.61 tons) is about three times larger than the expected steady state value. This peak arises from the initial flow, which strikes the deflector much like a piston and then must push the surrounding stationary air out of the way.

The input file used to set up this problem is given in Fig. 12. The calculation was run on a CDC CYBER 855 computer and took 20.3 min of CPU time to reach a problem time of 9.19 ms.

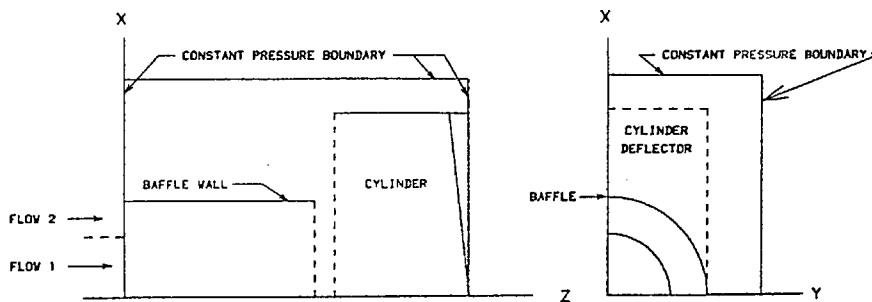


Fig. 1. Schematic of problem geometry.

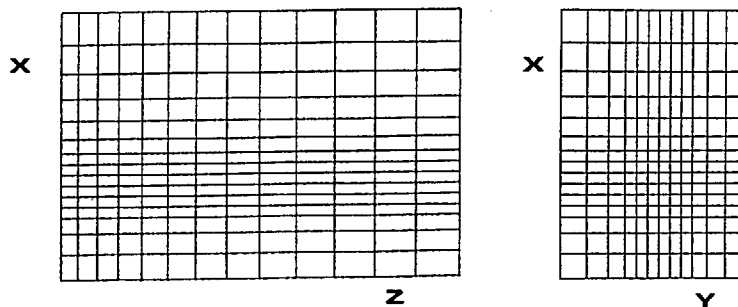


Fig. 2. Mesh used in calculations.

Fig. 3. Shaded region indicates Flow 2 input area. Outside stepped-boundary surface of shaded region coincides with cylindrical baffle approximation.

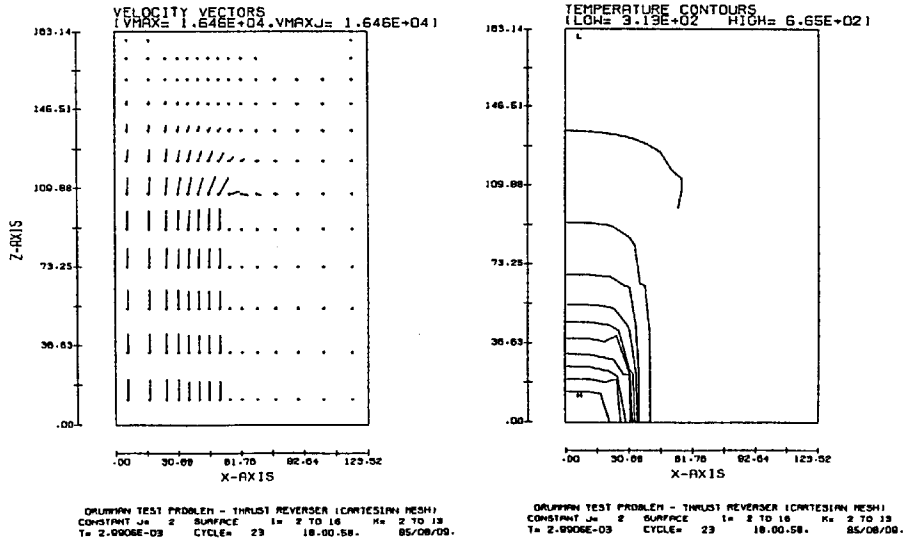
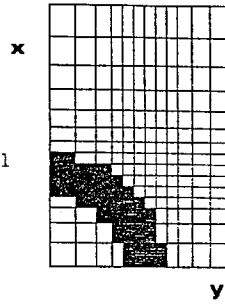


Fig. 4. Early time in transient (3 ms) shows developing flow and temperature contours. Vectors are drawn from the center of each cell with length and direction proportional to the local velocity. Units are cgs and $^{\circ}\text{K}$.

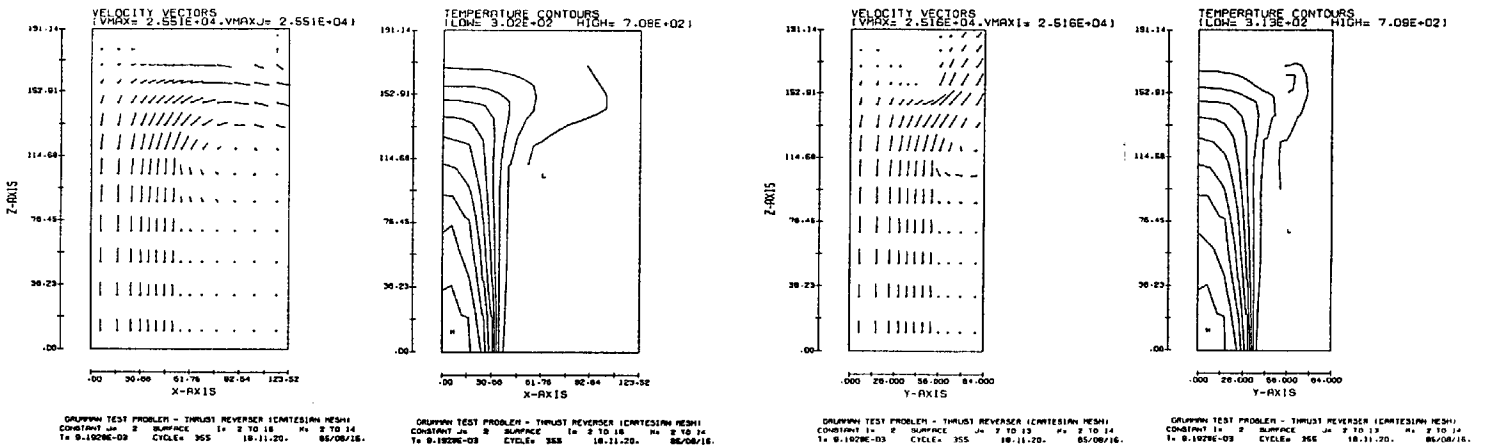


Fig. 5. Flow and temperature distributions at 9.2 ms in $y=0$ plane of symmetry. Units are cgs and $^{\circ}\text{K}$.

Fig. 6. Flow and temperature distributions at 9.2 ms in $x=0$ plane of symmetry. Units are cgs and $^{\circ}\text{K}$.

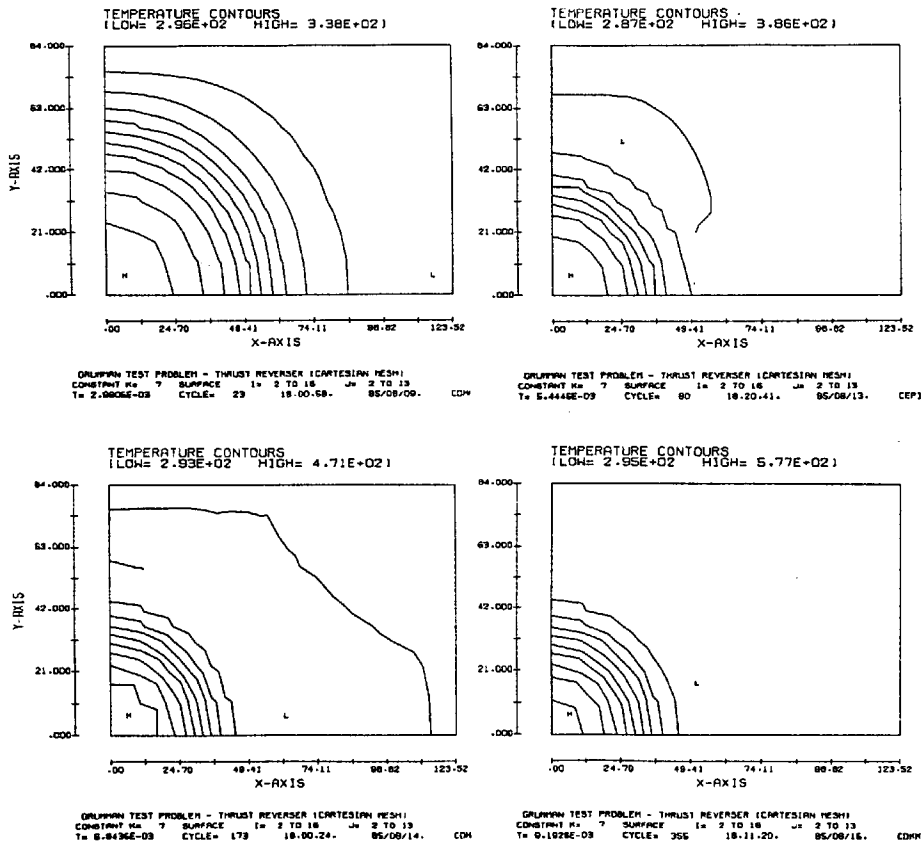


Fig. 7. Development of temperature profile across end of cylindrical baffle. Times are: 3 ms top left, 5.4 ms top right, 6.8 ms bottom left, and 9.2 ms bottom right. Units are $^{\circ}\text{K}$.

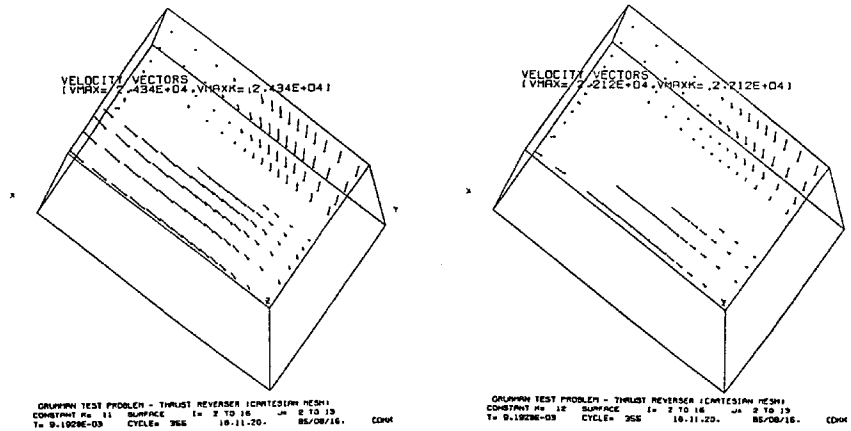


Fig. 8. Perspective of velocity field at 9.2 ms in $z=62.2$ in. plane at left and $z=66.5$ in. plane at right.

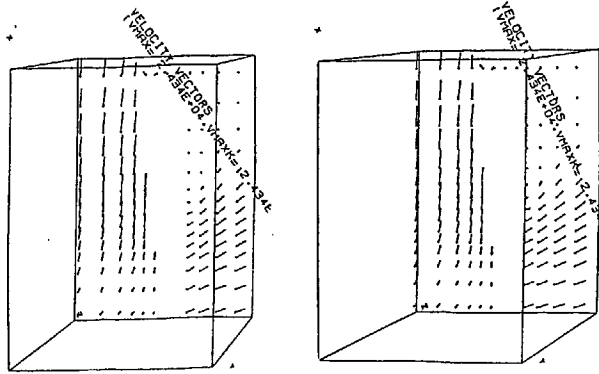


Fig. 9. Stereo view of velocity field in $z=62.2$ in. plane at 9.2 ms.

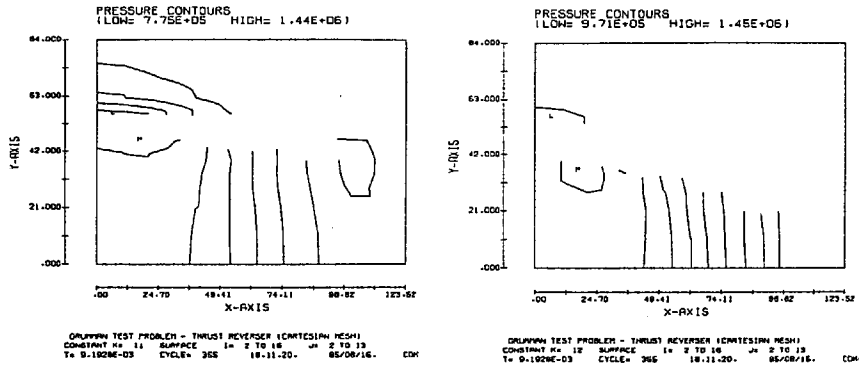


Fig. 10. Pressure contours at 9.2 ms in $z=62.2$ in. plane at left and $z=66.5$ in. plane at right. Units are dynes/cm².

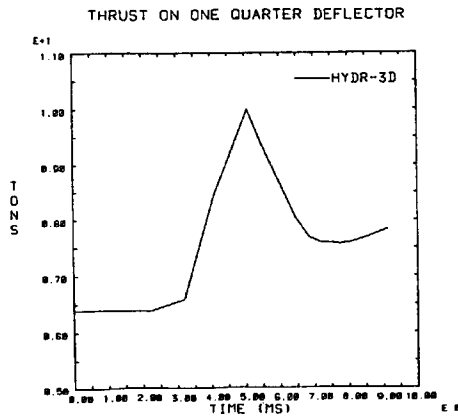


Fig. 11. Time history of force on one quarter of the thrust deflector.

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>>>>> FILE GRTEST <<<<<<

GRUMMAN TEST PROBLEM - THRUST REVERSER (CARTESIAN MESH)
#XFUT
HPLTDT=.001,
CYL=0.0,          NMAT=2,          ITMAX=25,
IRFR=10,         JBKPR=10,         KTPR=3,
TWFIN=.02,      DELT=7.E-5,       LPR=2,
IAF=2,          ICMPRS=1,         IPDIS=0,
WS=6,           WT=5,             WR=5,          WBK=5,
IMF=1,          MUI=7.5,         EPSI=5.0E-3,
RMRHO=1.41,     RMRHOE=1.41,
TIMBCT(1)=1.0E+10,
PBCT(1,2)=1.013E+6, FBCT(1,2)=0.0,          TBCT(1,2)=293.15,
PBCT(1,3)=1.53E+6,  PBCT(1,5)=1.415E+6,  PBCT(1,6)=1.013E+6,
WBCT(1,3)=1.510E+4, WBCT(1,5)=1.707E+4,  WBCT(1,6)=0.0,
FBCT(1,3)=0.0,     FBCT(1,5)=0.0,     FBCT(1,6)=0.0,
TBCT(1,3)=335.37,  TBCT(1,5)=752.,    TBCT(1,6)=293.15,
FBCT(1,4)=0.0,     PBCT(1,4)=1.013E+6,  TBCT(1,4)=293.2,
#END
#MESHGN
NKX=2,
  XL(1)=0.0,      XC(1)=33.5,      XL(2)=53.75,
                  XC(2)=53.75,  XL(3)=123.52,
  NXL(1)=4,      NXR(1)=4,      DXMN(1)=5.0,
  NXL(2)=0,      NXR(2)=7,      DXMN(2)=5.125,
NKY=2,
  YL(1)=0.0,      YC(1)=33.5,     YL(2)=53.75,
                  YC(2)=53.75,  YL(3)=84.0,
  NYL(1)=4,      NYR(1)=4,      DYMN(1)=5.0,
  NYL(2)=0,      NYR(2)=4,      DYMN(2)=5.125,
NKZ=1,
  ZL(1)=0.0,      ZC(1)=191.135,  ZL(2)=191.135,
  NZL(1)=13,     NZR(1)=0,      DZMN(1)=8.0,
#END
#OBS
NOBS=2,
CX2(1)=-0.0245,  CY2(1)=-1.0,    CZ2(1)=-0.9756,
CXZ(1)=-0.3090,  CX(1)=39.39,    CZ(1)=251.16,
CC(1)=-13276.93, YO(1)=53.746,  YHO(1)=-1.0,
ZO(1)=116.84,   ZHO(1)=1.0,
CX(2)=-1.0,     CC(2)=104.394,  IOH(2)=0,
#END
#FL
#END
#BF
IBFO(1,1)=1,
NBAFS=1,
BCX2(1)=1.0,    BCYZ(1)=1.0,    BCC(1)=-2888.676,
BZO(1)=105.664, BZH0(1)=-1.0,
#END
#TEMP
TEMP1=293.15,
#END
#GRAPHIC
NWINF=1,        KFZB(1)=8,
XEA(1)=150.,    YEA(1)=200.,    ZEA(1)=-1200.,
NCPLTS=5,
JC2(1)=2,      KONTYP(1)=5,
IC2(2)=2,      KONTYP(2)=5,
KC1(3)=11,     KC2(3)=11,
KC1(5)=7,      KC2(5)=7,      KONTYP(5)=5,
KC1(4)=12,     KC2(4)=12,
NVPLTS=4,
KV1(1)=12,     KV2(1)=12,     IPERV(1)=2,
KV1(2)=11,     KV2(2)=11,     IPERV(2)=2,
JV2(3)=2,
IV2(4)=2,
#END
#PARTS
#END

```

Fig. 12. Input file for HYDR-3D used to run this problem.