Overview of the 2D and 3D Finite Element Studies versus Experimental Results of a Solid Propellant Engine Performances under Cycling Loading Effect

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Abstract: - The article will summarize few of the achievements after the experimental and computational research on both 2 D axis symmetric and 3 D axis symmetric Finite Element modeling of the flow inside a solid propellant rocket engine with a specific axial distribution of the propellant's material temperature generated by the long run flight vibrations. The solid propellant was assumed to be a vascoelastic material under cycling loading. The 2D and 3D modeling results of the rocket engine's internal flow parameters and performances will be evaluated and compared with few of the performed experimental results.

Key-Words: rocket engine, 2D and 3D CFD simulations, vascoelastic material, flow parameters

1 Introduction

The scope of this article will be to briefly conclude over some of the qualitative results in respect with same authors papers presented at 2007 WSEAS [6] and 2008 WSEAS [7] in Greece. The 2D and 3D axis symmetrical CFD modeling, versus engine parameters and overall performance results will be reviewed, based on a new procedure at the early design stages of the solid rocket engines in the Bucharest's Technical Military Academy, next to the necessary validation procedures matters of the CFD models based on experimental data.

2 Problem Formulation

The solid propellant used as the fuel for the long run rocket engines was assumed as a viscoelastic material. Considering the high-speed of the space rocket long run engine, or a supersonic carrier, the solid fuel was proved to be a possible subject for cycle loading due to high speed and long term flight vibrations. Heating of the solid propellant under such conditions due to vibration near a resonance frequency in certain conditions may lead to melting, or material failure before a severe damage or explosion, or change in the rocket engine performances. The objective of this initial academic study was to evaluate the temperature distribution along the viscoelastic rod (or the solid propellant engine) under a such particular case and that was done using the governing equations (see also [2]):

- the energy balance equation;
- the equation of motion;
- the stress-strain relationship for induced vibrations;

The governing equations of the problem were next:

$$\frac{d^2\sigma_1}{dx^2}+\omega^2\rho(J_1\sigma_1+J_2\sigma_2)=0 \tag{1}$$

$$\frac{d^2\sigma_2}{dx^2}+\omega^2\rho(J_1\sigma_2-J_2\sigma_1)=0 \tag{2}$$

$$\rho C(\frac{\partial T}{\partial t})=\frac{\partial}{\partial x}(K\frac{\partial T}{\partial x})+\frac{\omega}{2}J_2(\sigma_1^2+\sigma_2^2) \tag{3}$$

Tormey and Britton in [1] conducted various vibration tests on various solid fuel families and revealed that the heating of the solid propellant due to vibrations increased the material temperature significantly.

Based on that temperature distribution along the axis of the solid propellant, an initial 2D CFD study [6] was employed for calculation of the initial rocket engine's internal flow parameters, like velocity, pressure and temperature, versus overall performances like thrust, considering two main case studies:

1. with variable axial temperature distribution from ***x=0*** to ***x = l*** (***l*** is the lenght of the solid propellant fuel), or *T = var*;
2. with cosntant temperature of the solid rocket propellant fuel, or *T=const*.

2.1 Special analyzed case with variable axial temperature distribution

As was described in [2] and [6] the following equation for the thermal conductivity of the solid rocket propellant was assumed in a linear form, as follows:

$$K = C_1 - C_2 T \qquad (4)$$

And that will change the form of the energy equation, as next:

$$C_1 \frac{\partial^2 T}{\partial x^2} - C_2 \frac{\partial}{\partial x}\left(T \frac{\partial T}{\partial x}\right) + \frac{\omega}{2} J_1(\sigma_1^2 + \sigma_2^2) \qquad (5)$$

where ρ is the mass density**,** ***C*** the specific heat, ***J1*** the storage modules, ***J2*** the loss modules, and ***σ1*** and ***σ2*** the real and imaginary parts of stress amplitude ***σ***, respectively.

3 Problem Solution

Fig 1. – Solid Propellant Rocket Engine - DUT

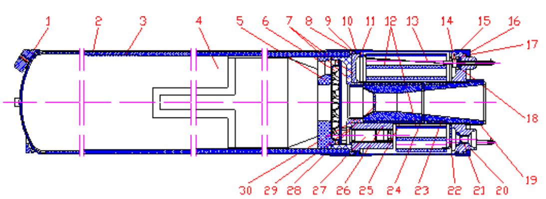

Fig. 1. Picture of the rocket engine under test

3.1.1 Analytical Model

To simulate the long run solid rocket propellant, and calculate de axial distribution of temperature, the academic study further considered as equivalent the vascoelastic rod, insulated on its lateral surface, as can be seen in Fig.2, and assumed also like a simplified mechanical equivalent model of the rocket engine.

As far one end of the vascoelastic rod stays free, the other end was attached to an experimental vibrator desk, able to run a vibration bandwidth from 1.0 kHz up to 100 kHz.

The vibrator will have a prescribed stress given by next relation:

$\sigma = \sigma_o \cos \omega t$

with:

- σ known as the stress amplitude;
- ω the frequency;
- ***t*** the time.

The convective boundary condition was assumed at ***x = 0*** , while ***H*** is the surface conductance and ***K*** is the thermal conductivity of the solid propellant material.

The initial temperature ***T₀*** of the vibrator desk was assumed to be constant.

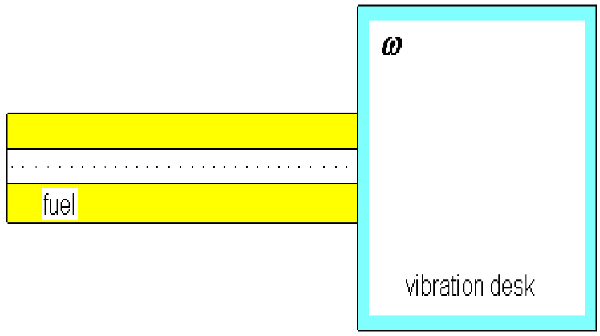

Fig. 2 – Mechanical equivalent model

3.1.2 Initial temperature axial distribution for the 2D and 3D CFD studies

For the academic long run solid rocket engine case and study, it was important to evaluate the consequences of the axial rising temperature in the solid propellant fuel, in order to recalculate the changes of the internal flow parameters and performances of the rocket engine.

The analitical model and initial study results were listed in the Table 1, from ***x=0*** to ***x = l*** and were assumed like the distribution of one possible worst case scenario axial temperatures distribution due to mechanical vibrations developed from an initial ambiental temperature of 38 [grd. C] of the vasoelastic rod, or the equivlent long run solid propellant rocket engine under test (DUT).

In order to refine the whole case, based on initial analytical model, the vascoelasic rod, or the propellant length (***l***) was divided in the selected case study in 21 initial cells and finally refined in 40 cells.

The assumption that the temperature will be constant by radius and variable by axial length in [7] followed the initial case study [6] too, when the axial temperature distribution assumed and studied first as a constant and second like a variable parameter too, due the development of the analytical model.

All the Table 1 data were used as input for both further 2D and 3D CFD employed studies, using FLUENT[R] ver 6.2 software package.

Table 1

Section	x/l	T [grd.F]	T [grd.C]	T [grd.K]
1	0.00	100	38	311
2	0.05	150	66	339
3	0.10	250	121	394
4	0.15	350	177	450
5	0.20	400	204	477
6	0.25	500	260	533
7	0.30	350	177	450
8	0.35	250	121	394
9	0.40	200	93	366
10	0.45	150	66	339
11	0.50	100	38	311
12	0.55	150	66	339
13	0.60	250	121	394
14	0.65	350	177	450
15	0.70	400	204	477
16	0.75	500	260	533
17	0.80	350	177	450
18	0.85	250	121	394
19	0.90	200	93	366
20	0.95	150	66	339
21	1.00	100	38	311

3.1.3 2D and 3D simulation results

The 2D distribution of the temperature inside the engine when $T = cst$ is shown in the next figures:

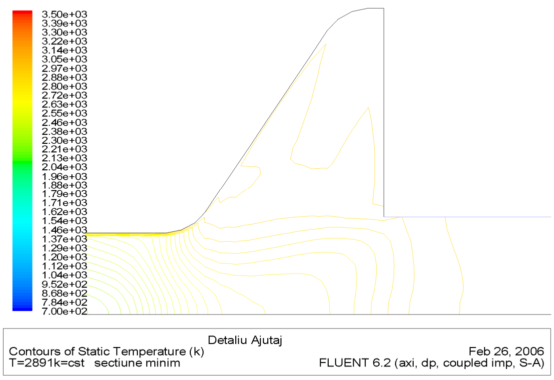

Fig. 3 – 2D study revealing peak $T = 2{,}930\ ^{o}K = cst$

And consequently the simulation for T = variable case will bring next results:

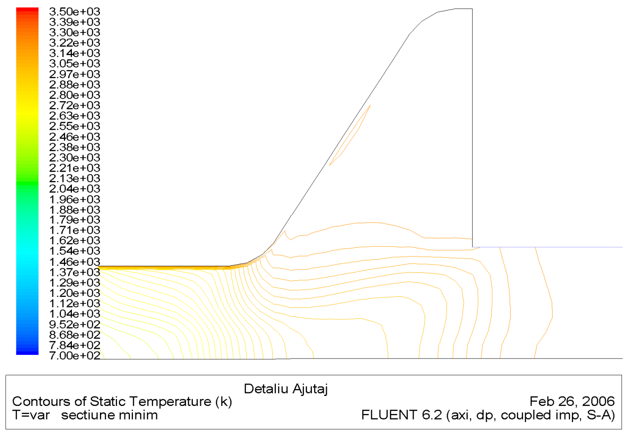

Fig.4 – 2D study revealing peak $T = 3{,}430\ ^{o}K$

The 2D pressure distribution in the nozzle area is almost the same in both cases, as it was supposed to be found, as can be seen in the Figure 5 and Figure 6.

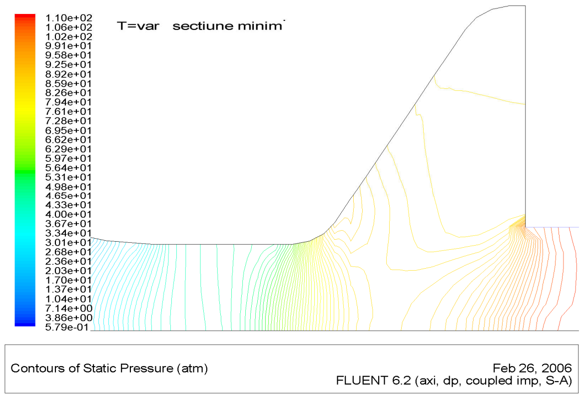

Fig. 5 – 2D study, $T = var$, presure distribution

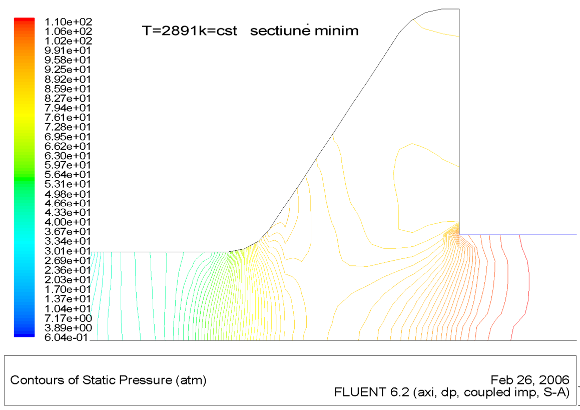

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Fig. 6 – 2D study, $T = cst$, presure distribution

The 2D study velocity distribution results in the nozzle area was almost the same in both cases, with very little differences – 6.6%, including the significant +18% rise in burning temperature, as can be seen in the Figure 7 and Figure 8.

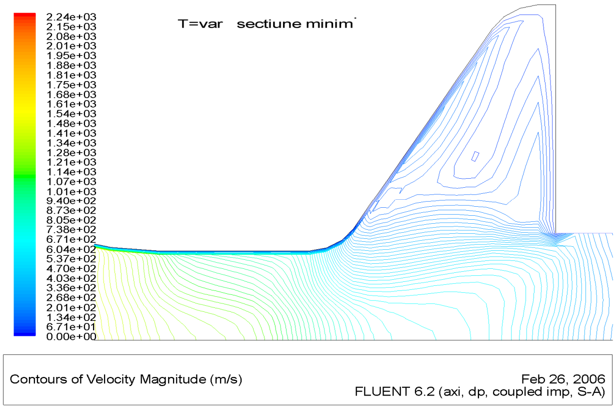

Fig. 7– 2D study, T = *var*, velocity distribution

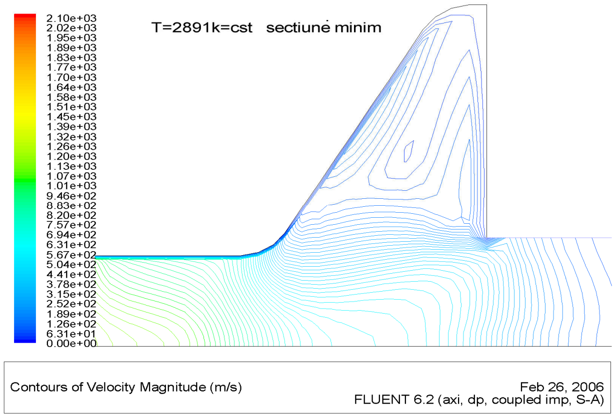

Fig. 8 – 2D study, T = *cst*, velocity distribution

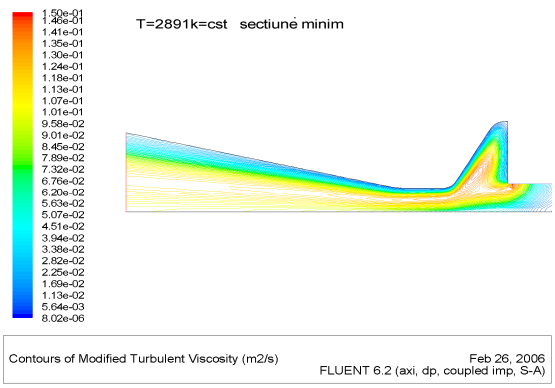

Fig. 9 – 2D study, T = *cst*, turbulence distribution.

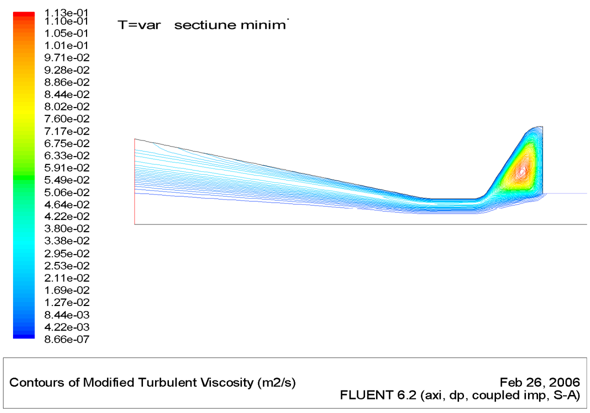

Fig. 10 – 2D study, T = *var*, turbulence distribution

The 3D distribution of the temperature inside the engine when T = *var* is shown in the next figures:

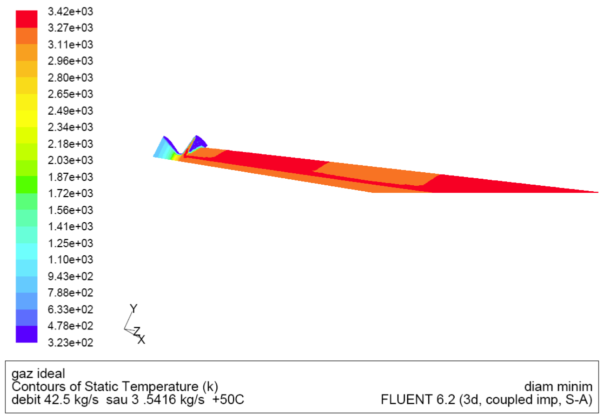

Fig. 11 – 3D study initial flow temperatures because of the initial assumed temperature distribution inside the rocket engine as Table 1

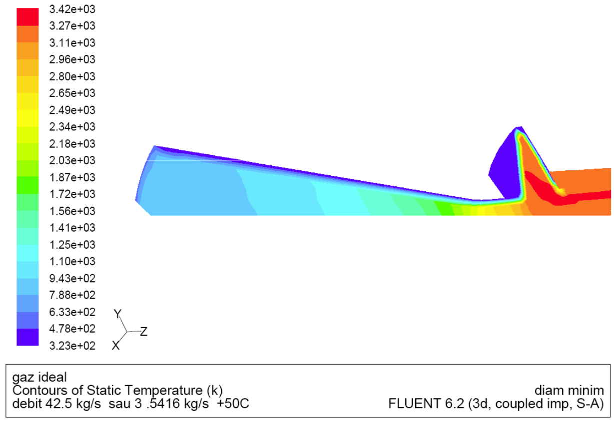

Fig. 12 – 3D study in the nozzle area flow temperatures like results of the initial temperature distribution inside the rocket engine

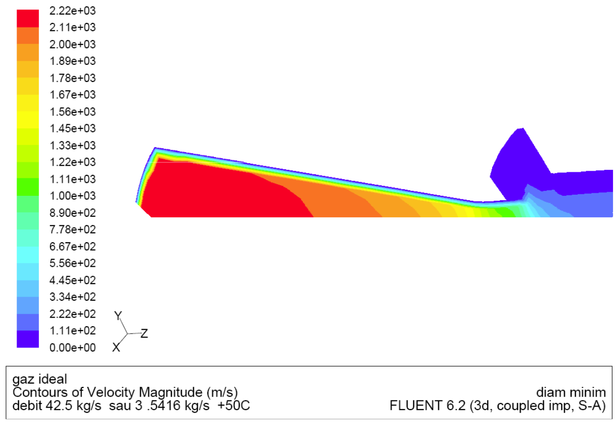

Fig. 13 – 3D study in the nozzle area velocity distribution like results of the initial temperature distribution inside the rocket engine

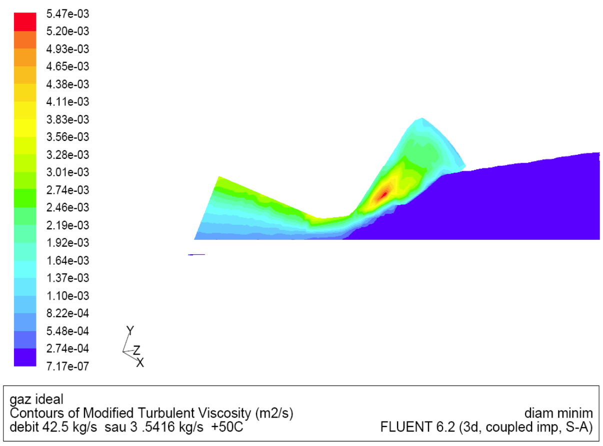

Fig. 14 – 3D study in the convergent nozzle area turbulence issues like results of the initial temperature distribution inside the rocket engine

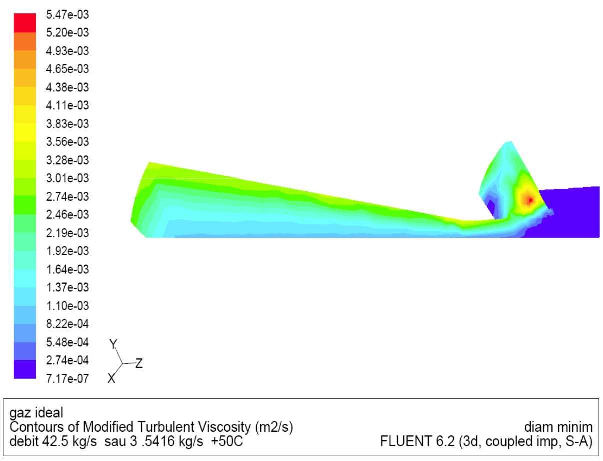

Fig. 15 – 3D study in the divergent nozzle area turbulence issues like results of the initial temperature distribution inside the rocket engine

3.1.4 Validation of the initial 2D and 3D results

Validation of the initial 2D and 3D axis symmetrical CFD results presented in the 1st and 2nd WSEAS papers [6] and [7] were one of the important issues concerning our academic approach methodology in getting fast, but controlled accurate enough type of numerical results and improve the speed in development of the early design stages of the long run solid propellant rocket engine. Six separate experimental engines were fired on the experimental bed test platform at extreme temperatures of -50 deg.C and +50 deg.C and acquired data were used to evaluate and validate both 2D and 3D CFD results. See Tables 2 and 3 for some raw experimentally collected data for Thrust Force (***F***) and Tables 4 and 5 also for some other raw experimentally collected data for inside pressure of the experimentally rocket engines tested for validation check-up procedures.

Results of the 3D CFD study revealed first the (***F***) thrust and (***P***) pressure maximal values possible and second how the velocity, turbulence and temperature of the rocket engine's internal flow will change, in the worst case scenarios of possible variable temperature among the axis of the solid propellant, as was acknowledged from the Table 1 input data.

Exp Table 2 + 50 C

Time [s]	P fluent [atm]	P exp1 [atm]	P exp2 [atm]	P exp3 [atm]	Pm exp +50 C [atm]
0.1	97.3	96.3	101.3	81.1	92.9
0.148		95.0	100.5	100.5	98.7
0.2		96.9	102.8	112.5	104.1
0.5		98.3	103.4	105.4	102.3
1.0		97.1	101.3	105.9	101.4
1.3	87.3	93.0	98.5	103.0	98.2
1.5		92.7	97.8	101.8	97.4
2.0		87.6	93.2	97.8	92.9
2.08	87.1	86.0	92.0	95.0	91.0
2.5	87.1	83.6	89.2	93.2	88.7
3.0		79.5	85.6	87.6	84.3
3.5		75.0	80.0	83.1	79.4
4.0		69.4	74.5	77.5	73.8
4.3		51.2	29.9	68.9	50.0

Exp Table 3 + 50 C

Time [s]	Ft fluent [kN]	F exp1 [kN]	F exp2 [kN]	F exp3 [kN]	Fm exp +50 C [kN]
0.1	31.8	31.2	25.9	19.0	25.4
0.148		31.6	25.8	27.9	28.4
0.2		31.8	25.8	26.0	27.9
0.5		32.3	25.7	26.2	28.1
1.0		31.5	24.5	25.7	27.2
1.3	33.5	30.9	24.0	25.5	26.8
1.5		30.2	23.4	24.5	26.0
2.0		28.6	22.0	23.6	24.7
2.08	31.6	28.3	21.9	23.4	24.5
2.5	31.2	27.0	20.5	22.8	23.4
3.0		25.5	19.0	22.0	22.2
3.5		24.5	17.5	21.1	21.0
4.0		23.2	14.2	20.0	19.1
4.3		8.9	7.0	19.2	11.7

Exp Table 4 - 50 C

timp [s]	P fluent [atm]	P test1 [atm]	P test2 [atm]	P test3 [atm]	Pm - 50 C [atm]
0,10	157,3	56,7	59,5	58,8	58,4
0,18		73,8	74,5	67,0	71,8
0,20		75,0	76,0	75,0	75,3
0,50		75,5	89,3	88,2	84,3
1,00		88,2	86,2	85,1	86,5
1,50		83,1	85,2	84,1	84,1
1,59	69.4	82,5	84,5	83,5	83,5
2,00		79,0	83,7	82,6	81,8
2,50		73,0	81,1	80,0	78,0
2,54	69,4	71,2	79,5	79,0	76,6
3,00		66,4	78,5	77,5	74,1
3,05	69,6	64,2	77,8	75,0	72,3
3,50		59,8	75,5	74,5	69,9
4,00		52,2	71,4	70,4	64,7
4,50		42,8	68,3	67,4	59,5
5,00		39,5	63,7	62,8	55,3
5,20		37,5	56,0	55,2	49,6

Exp Table 5 - 50 C

timp [s]	Ft fluent [kN]	F test1 [kN]	F test2 [kN]	F test3 [kN]	Fm -50 C [kN]
0,10	25,3	14,0	16,4	13,4	14,6
0,18		24,4	24,9	18,5	22,6
0,20		24,5	27,0	19,0	23,5
0,50		24,7	29,5	23,8	26,0
1,00		28,6	25,1	22,4	25,4
1,50		28,0	24,8	22,0	24,9
1,59	25,2	27,8	24,5	22,0	24,8
2,00		26,7	23,7	21,3	23,9
2,50		24,6	23,0	20,7	22,8
2,54	25,1	24,5	22,5	20,5	22,5
3,00		22,5	21,9	19,9	21,4
3,05	24,9	22,1	21,5	19,5	21,0
3,50		20,2	20,1	19,3	19,9
4,00		17,5	19,0	16,8	17,8
4,50		15,0	18,3	16,0	16,4
5,00		13,1	16,9	14,0	14,7
5,20		12,4	14,2	12,0	12,9

The experimental distribution of measured data will be presented in the next two charts. Chart 1 will demonstrate the average variation of the measured Thrust (***Fm***) values of the rocket engine (average of the 3 experimental values collected at firing tests at -50deg.C with blue color and with magenta for the +50 deg.C. firing tests) as can be found in Table 3 and 5. Chart 2 will show the variation pattern of the average variation of the measured inside pressure (***Pm***) of the rocket engine, with same color code as Chart 1, and values found in Tables 2 and 4.

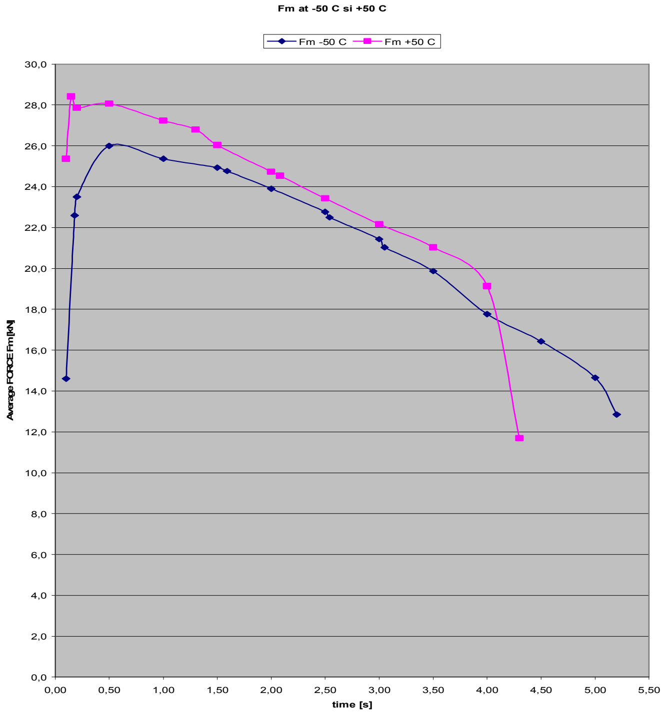

Chart 1 – variation of average F at -50 and +50 deg. C

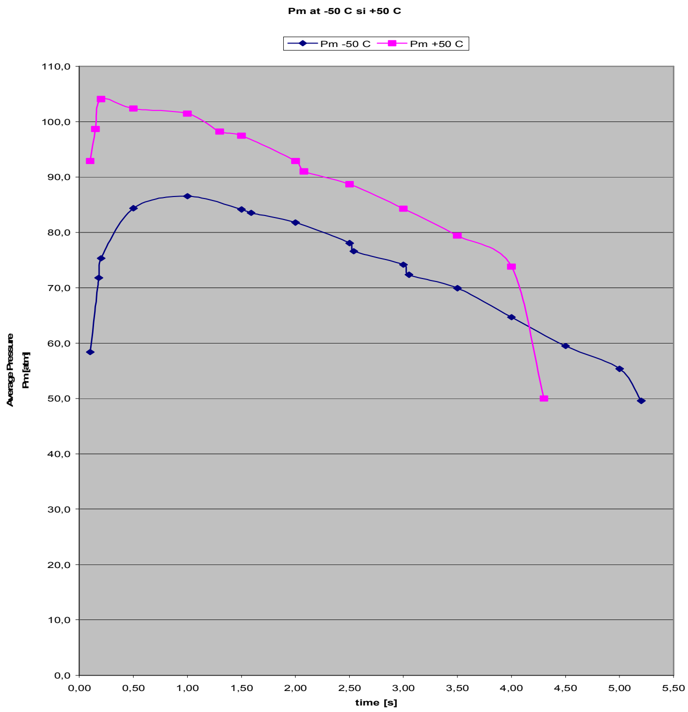

Chart 2 – variation of average P at -50 and +50 deg. C

A new set of experimental values presented are the measured values of the inside pressure and thrust force of the 3 test engines sets at extreme temperature values, as -50 deg.C and +50 deg.C. The dispersion of the experimental data will be interesting to be reviewed versus CFD results validation procedures.

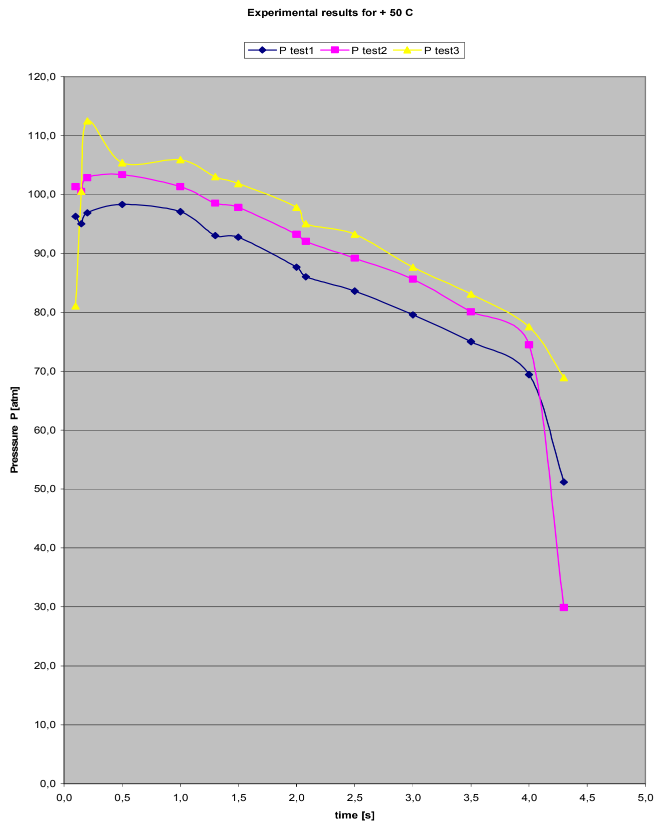

Chart3 - measured values for inside pressure at +50 deg.C

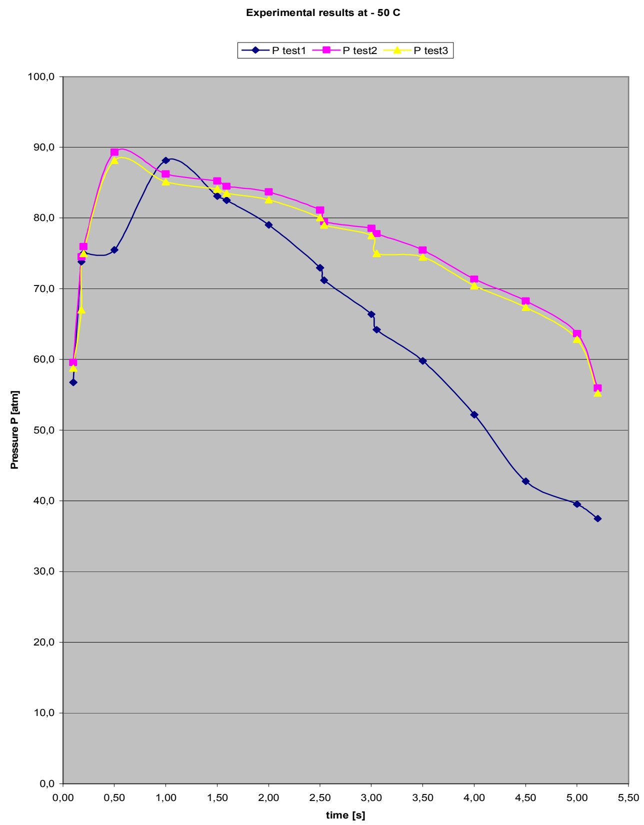

Chart5 - measured values for inside pressure at -50 deg.C

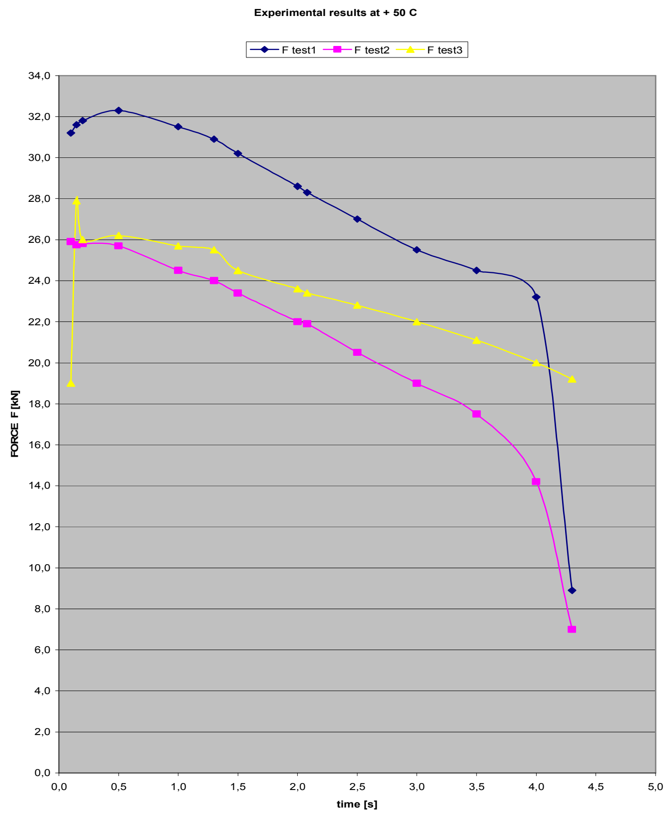

Chart 4 – measured values for thrust force at +50 deg C

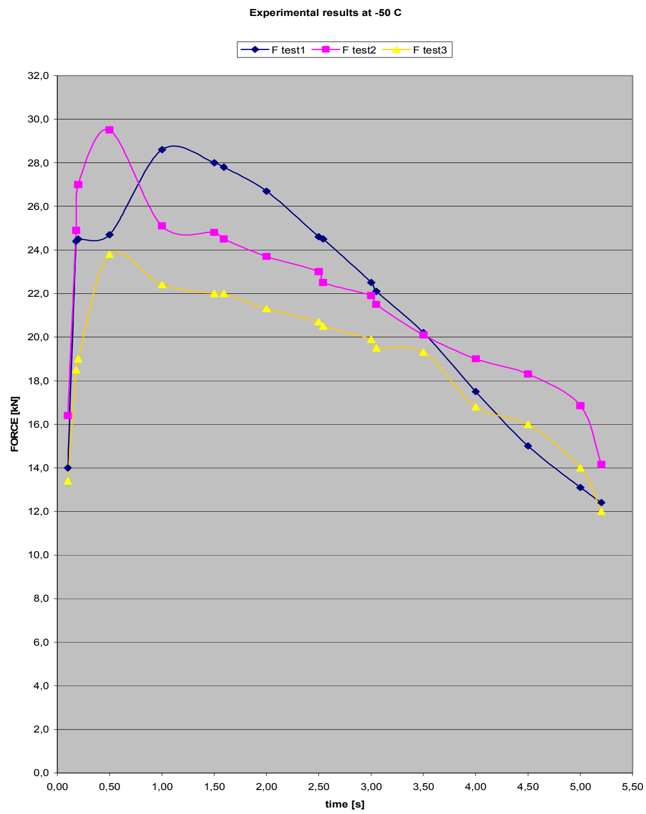

Chart 6 – measured values for thrust force at -50 deg C

3.1.5 The importance of the 3D FLUENT^R simulations and results

The 3D axis-symmetrical single precision modeling and simulation employed some compromise between a large and expensive hardware versus real life design time constraints. There was necessary a significant amount of single processor computer time due up to 225k iterations for convergence. Comparing with the initial 2D axis-symmetrical double precision previous computational task [6], there was a difference between 5 to 10 times in more computer machine and modeling effort in case of 3D study. The difference in (***F***) thrust and (***P***) inside pressure maximal engine values results are below 5% in all of the cases, including values for velocity distribution and turbulence, under the same temperature initial data (see Figures 4 to 15).

4 Conclusions

4.1. Validation of various CFD results

The 2D study was demonstrated to be efficient enough for a fast check-up and performance evaluation inside the engine flow. Proved to be very convenient for early design stages and evaluation of any early project, both academic and industry.

The 3D study highlighted the first possible hidden "hot spots" of the initial engine design, way before spending more time and money in manufacturing prototypes, also helping to conclude the mechanical design before any prototype and first experimental live evaluation tests on the Bed Test Platform. In respect with 3D axis symmetrical output results of the CFD study, it was proved that the difference in (***F***) thrust and (***P***) inside pressure maximal values results next to experimental measurements are below 5% in all of the cases, including values for velocity distribution and turbulence, under the same initial data. The experimental results will validate the both 2D and 3D CFD results in a maximum 15% maximum relative error envelope as was the initial target and the validation procedures of the project will tell if there will be a need for more accuracy and improved CFD modeling.

4.2. Validation procedures review

The authors will strongly advice any similar early development to employ at least a 2D CFD calculation during the early design stages and also to start the development of a procedure program like a way to achieve an indispensable tool in the validation of propulsion technology advances for any reactive propulsion system. The advantage will be a fast and cheap approach because of using in early stages CFD modeling, with validation on measurement and diagnostic methods that are continuing to be used in most of the world's rocket engine research programs and are applicable to other similar test and evaluation scenarios. Accordingly with NASA standards, their Technology Test Bed highly instrumented engine employs over five times the number of measurements used for an acceptance test of a flight engine. Only under such circumstances the ground tests will confirm the requested amount of detailed knowledge of the initial estimated CFD performance of rocket engines under widely varying conditions.

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