RESEARCH ON SMALL TURBOJET ENGINES AT THE ROYAL MILITARY ACADEMY OF BELGIUM

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ABSTRACT

High speed and high altitude UAV and MAV flight requires certain qualities of the installed engine(s). The use of turbojets for this purpose is justified, though, the engines can lack performance, which might be countered with inlet precooling. This paper describes the research done at the RMA on inlet precooling. Mainly the influence of the precooling on the thrust and the TSFC of the SR-30 mini turbojet are covered. Here, the precooling is obtained through injection of liquid nitrogen in the engine inlet. Theory and experiments are compared and the influence of icing on the performance of the engine is discussed.

BIOGRAPHY

F. Buysschaert graduated at the K.H.B.O. academy in Ostend as an engineer. Now he is a research engineer at RMA in the field of UAV propulsion.

USED SYMBOLS

indices

' : with precooling
1 : in front of engine compressor
2 : aft compressor station
3 : in front of engine turbine
5 : exhaust nozzle station
a : ambient
g : combustion gas
j : jet ; corresponding with 5
t : stagnation
cc : combustion chamber
id : ideal
is : isentropic
C : compressor
T : turbine
N2 : nitrogen

abbreviations

g : adiabatic exponent
h : cooling efficiency [1]
h_{cc} : combustion chamber efficiency [1]
$h_{is,C}$: compressor isentropic efficiency [1]
$h_{is,T}$: turbine isentropic efficiency [1]
q : heating ratio [1]
l_{cc} : pressure drop in combustion chamber [1]
p_c : compressor pressure ratio = p_{t2} / p_{t1} [1]
c_p : specific heat capacity [J/kgK]
d : fuel to air ratio
$\dot{m}$: mass flow inlet air [kg/s]
$\dot{m}'$: mass flow inlet air with precooling [kg/s]
$\dot{m}_f$: fuel flow [kg/s]
p : pressure [Pa]
p_t : stagnation pressure [Pa]
v : gas velocity [m/s]
qci : fuel lower heating value [J/kg]
A_i : cross-section i
EGT : exhaust gas temperature [K]
LN2 : liquid nitrogen
L_v : latent heat [J/kg]
M : Mach number [1]
MAV : mini air vehicle
N2 : nitrogen
RMA : Royal Military Academy of Belgium
RPM : rotation speed [1/min]
RR : ram recovery [1]
T : temperature [K]
TIT : turbine inlet temperature [K]
T_N : thrust [N]
TSFC : thrust specific fuel consumption [kg/(daN.h)]
$TSFC_{N2}$: LN2 thrust specific fuel consumption [kg/(daN.h)]
UAV : unmanned air vehicle
UCAV : unmanned combat air vehicle

1. PURPOSE OF THE STUDY

Not all small sized unmanned aerial vehicles, so called UAV's, are intended to be used at low speed and low altitude. Some of them, as the Sperwer HV of Sagem, are designed to fly at high speed (M 0.6) and high altitude (more then 30.000 ft). Those requirements can cause trouble finding an appropriate engine for the aircraft, especially for hot days or hot climates, since there are not much small scaled engines on the market and constructing a tailor-made one would boost development costs. When we are dealing with high altitudes and speeds, a turbojet will pop up as a favourite because of its low weight, dimensions and high exhaust velocity, allowing high-speed flight. When there is a lack of thrust or efficiency, *inlet precooling* could be a solution to that problem. At the RMA, extensive research is done on finding out what influences inlet precooling has on the performance of a mini-turbojet. The purpose of this study is to evaluate the impact of inlet precooling on the performance of a mini-turbojet and to get familiar with the problems who will raise such as icing. The results are given in this paper.

2. THE SR-30 MINI-TURBOJET

To investigate the impact of inlet precooling on a turbojet, the Royal Military Academy of Belgium uses a SR-30 mini-turbojet, made by Turbine Technologies Ltd., Wisconsin, USA (fig. 1 and 3).

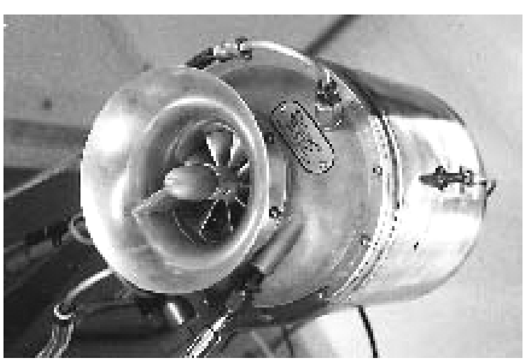

fig. 1 : the SR-30 turbojet

This turbojet is a 171 mm by 273 mm engine and it produces at its maximum rating 100 N of thrust, when the standard exhaust nozzle is installed. The engine has the ability to run on different fuels, though, all tests are done with JP-8. It consists of a bellmouth inlet, a centrifugal compressor, a reversed combustion chamber, an axial turbine and a fixed convergent nozzle.

This engine is installed on a Minilab testbench (fig.2). The testbench allows engine-control and provides fuel, oil and air to the engine. The data acquisition is obtained with a National Instruments SCXI chassis and displayed with LabView.

fig. 2 : the RMA MiniLab test bench

3. THERMODYNAMICAL IMPACT OF INLET PRECOOLING ON ENGINE PERFORMANCE

This part will discuss the thermodynamical impact inlet precooling has on the thrust and thermal efficiency of a turbojet. The reader is advised to notice the annotations used in fig. 3 to determine the different stations in the engine. This is necessary to have a better understanding of the perturbed air in front of the inlet, 1 is the station just in front of the compressor, 2 is the station after the compressor, 3 is the station in front of the turbine, 4 is the station just behind the turbine and 5 (also annotated by j) is near the engine outlet.

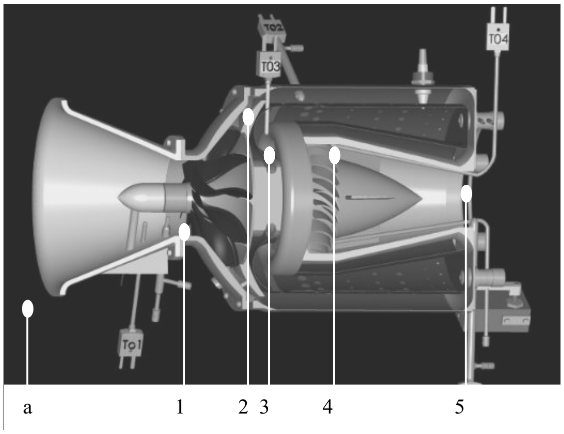

fig. 3 : the station designation

A very helpful tool to calculate the thrust theoretically, is the reduced net power W_{red}. Buysschaert (1) derived the following equation :

$$W_{red} = \eta_{is,T}\{\eta_{cc}[\theta - \psi] + \psi\}\left\{1 - \left[\frac{1}{RR(1-\lambda_{cc})\pi_c}\right]^{\frac{\gamma-1}{\gamma}}\right\} - \{\psi - 1\} \quad [1]$$

with

$$\psi = \frac{\pi_c^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{is,C}} + 1 \quad [2] \qquad \text{and} \qquad \theta = \frac{T_{t3,id}}{T_{t1}} \quad [3]$$

Also, a relation to find a value for the thermal efficiency was found :

$$\eta_{th} = \frac{W_{red}}{\theta - \psi} \quad [4]$$

Equations [1] and [4] are plotted in figures 4 and 5 respectively. It can be seen clearly that for a given pressure ratio, an increase in W_{red} can be obtained by increasing the heating ratio θ .

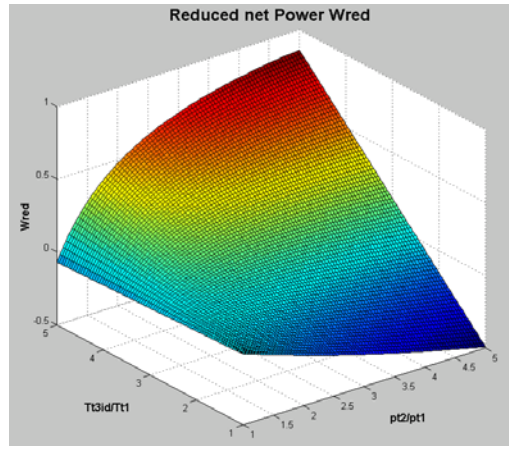

fig. 4

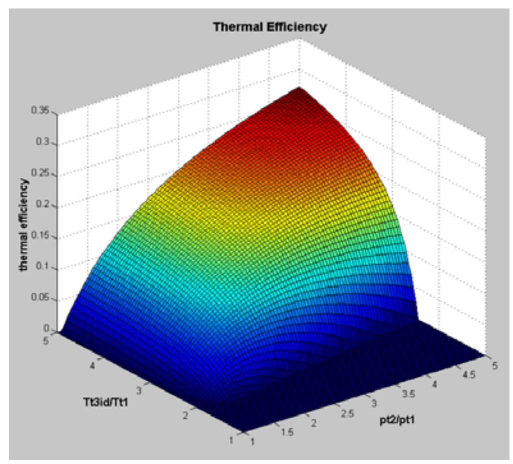

fig. 5

The efficiencies are based on real data of the SR-30 engine, obtained at RMA. They are given in table 1. We assume that all efficiencies remain constant in function of engine ratings and precooling level.

RR	$\eta_{is,C}$	$\eta_{is,T}$	η_{cc}	λ_{cc}
1	0.7	0.95	0.99	0.05

table 1

The first method to increase the net power is to inject more fuel, resulting in a higher TIT and θ . Though, there are temperature limits imposed by the combustion chamber, the turbine materials and lifetime considerations. Still, we can boost θ by decreasing the compressor inlet temperature T_{t1}. Consequently, higher thrust and thermal efficiency can be obtained.

It is obvious that an increase of the heating ratio θ is beneficial for the thrust. One can ask what will happen with θ presuming 4 different scenarios :

a) decrease of T_{t1} without changing the fuel flow
b) decrease of T_{t1}, keeping the fuel to air ratio d constant
c) decrease of T_{t1}, keeping TIT constant
d) decrease of T_{t1}, keeping EGT constant

Only cases a & b were considered theoretically, c & d followed from a & b.

__a) constant fuel flow with decreasing T_{t1}__

The main purpose is to find an equation that shows us whether an increase of θ can be obtained or not. Therefore we have to find a relation between TIT and T_{t1}.

When we consider a constant RPM, the assumption that the airspeed in front of the compressor v_1 remains constant, is plausible. Starting from the following combustor equation :

$$q_c.d = c_{pg}T_{t3id} - c_p.T_{t2} \qquad [5]$$

and applying the definitions of c_p, d and Castelli's law, the following relation can be derived :

$$T_{t3id} = T_{t1}.\psi + A T_{t1}^{\frac{\gamma}{\gamma-1}} \left(T_{t1} - B\right)^{\frac{1}{1-\gamma}} \qquad [6]$$

with

$$A = \frac{q_c.\dot{m}_f.(\gamma-1)}{\gamma.A_1.v_1.p_{t1}} \quad [7] \qquad \text{and} \qquad B = \frac{v_1^2}{2.c_p} \quad [8]$$

The first term of equation 6 characterizes the temperature increment due to the adiabatic compression of the air, the second term tells us how much the temperature will increase because of the heat generated by the combustion of the injected fuel. Figure 6 visualizes equation 6. The parameters A and B were calculated with the following values, derived from RMA experimental data :

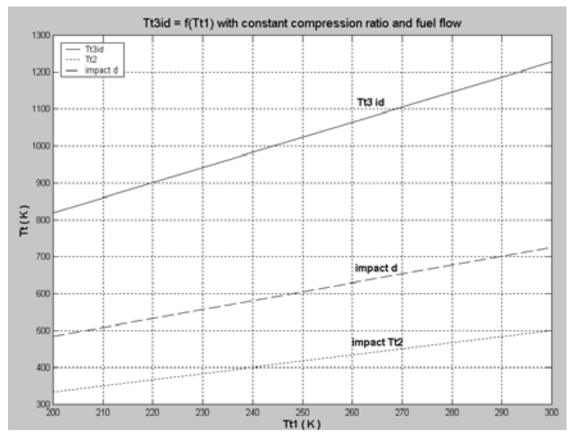

fig. 6

q_c	43,2 MJ/kg fuel
$\dot{m}_f$	0.00441 kg/s
γ	1.4
A_1	7390 mm_
v_1	30 m/s
p_{t1}	100900 Pa
c_p	1004 J/kgK
ψ	1.671

Figure 6 shows an apparently linear curve of T_{t3id} as a function of T_{t1}. Notify that the curve goes through the origin of the plot, which means that $T_{t3id} = f(T_{t1})$ can be written in the following simplified form :

$$T_{t3id} = K_1.T_{t1} \quad \text{or}$$
$$\theta = K_1 \qquad [9]$$

This equation is very useful, since it tells us that the heating ratio θ is a constant when we cool down the inlet air without addition of fuel. Applying the definition of the reduced net power :

$$W_{red} = \frac{net \quad available \quad power \quad \dot{W}_n}{\dot{m}c_p.T_{t1}} \qquad [10]$$

With mediocre chilling, the denominator of equation 10 remains more or less constant. Examining relations 1 and 10, one can see that W_{red} will consequently remain constant and $\dot{W}_n$ too.

As a result of this discussion, the conclusion is that precooling with a constant fuel flow is useless.

b) decrease of T_{t1} with a constant d

When inlet precooling is applied, the mass flow of air will increase. In order to keep d constant, one has to increase the fuel flow. Again, departing from relation 5, the following equation for $T_{t3id} = f(T_{t1})$ can be derived :

$$\theta = \frac{q_c.d}{c_p.T_{t1}} + \psi \qquad [11]$$

The use of precooling with a constant d seems very interesting, since a reduction of T_{t1} results in a rise of the heating ratio and consequently the thrust and thermal efficiency.

Since a constant fuel to air ratio involves a lower TIT with a lower inlet temperature, which can also be derived from equation 11, keeping TIT and EGT constant will boost the thrust and thermal efficiency as well, **if** the proposed efficiencies remain constant (or improve).

4. EXPERIMENTAL VALIDATION OF THE DERIVED EQUATIONS

There are many ways of cooling air, though only a few of them are economically justified and suitable to fit on an aircraft or UAV. The RMA chooses liquid nitrogen LN2 because of its ease of use, its chemical inertness, its low influence on air composition and last but not least its low temperature. It is also an interesting coolant when put on an aircraft. This because it is stand-alone. With a few valves and a dip, the nitrogen can keep itself cool, though with a small and continuous loss of its mass, since latent heat is necessary to maintain the liquid state.

One can cool air with LN2 in two ways : chilling the air actively by injecting LN2 directly in the airflow or passively by using a tube or plate heat exchanger. Research work is done using both methods, though passive cooling is still in the making. Thus, this paper will present the results of the active cooling only. The large advantage of this direct injection method is that the air pressure drop is very limited when precooling is used and zero in flight sequences without precooling.

4.1 Description of the cooling device

A low pressure 180L Ranger of Air Liquide supplied the liquid nitrogen (at 77 K). A 3m long flexible inox tube connected the ranger with the sintered bronze spray nozzle (fig.7). First tests showed that the injector had to be fixed above the centerline of the bellmouth inlet (fig.8). Consequently the engine sucked in all LN2. This was necessary since an approximation of the mass flow of nitrogen $\dot{m}_{N2}$ had to be measured. The only way of measuring $\dot{m}_{N2}$ is by gauging the mass of the ranger before and after the test. The explanation is that LN2 leaves the reservoir at 1.7 bar absolute pressure in the saturated state. Near the flexible tube the N2 finds itself in the state of

fig. 7

fig. 8

coexistence. Consequently, we cannot define the present amount of gas or liquid, excluding any type of flow meter.

4.2 Temperature T_{t1} measurement

The temperature T_{t1} was planned to be measured with a thermocouple type N. Unfortunately, the cooling of the air wasn't homogeneous. The nitrogen cooled just a small amount of air, which went as good as straight into the engine, without any vortical speed what was hoped for. Installation of an extra two thermocouples did not bring solace.
It became evident that with this type of injector, no direct gauging of T_{t1} was possible.
Though, with the knowledge of $\dot{m}_{N2}$, $\dot{m}$ and $\dot{m}$, which is the inlet air mass flow with precooling, and the air temperature T_{t1} without cooling, one can derive the temperature drop ($T_{ta} - T_{t1'}$) = ΔT_{t1} quite trustworthy. Three different calculation methods were examined. The first method uses enthalpies to derive the temperature drop. If we assume that the inlet air is dry, that only LN2 leaves the injector, that all the nitrogen is evaporated before entering the compressor and that only a small amount of nitrogen is injected, leaving the airspeed unaffected, the following equation may be used :

$$\dot{m}.c_{pa}.(T_a - T_{1'}) = \eta\ .(\ \dot{m}_{N2}.L_{v,N2} + \dot{m}_{N2}.c_{p,N2}.(T_{1'} - T_{N2})\ ) \qquad [12]$$

$T_{1'}$ can be calculated from relation 12. Since the static and the stagnation pressures are measured at the inlet, one can derive the gas velocity. Thereby $T_{t1'}$ can be obtained and consequently the temperature drop.
There was one objection against the use of this formula : $\dot{m}_{N2}$ was not gauged with high accuracy. Therefore a better calculation method had to be found. The new method is based on the assumption that the inlet airspeed, for a constant RPM, is independent of the inlet temperature. Additionally, one physical parameter has to be constant, regardless of the fact that precooling was applied. Examining the stagnation inlet pressure p_{t1} and the static inlet pressure p_1, the following phenomenon can be found (fig. 9). The stagnation pressure with and without precooling is more or less the same (very low friction losses due to N2-injection). Thus, the assumption that the stagnation pressure remains invariant may be justified. On the other hand, the difference between the static pressures is not significant, which leaves the method of calculating T_{t1} with a constant static pressure more or less acceptable. Furthermore, the latter theory is much easier to use, which will be proven here after.

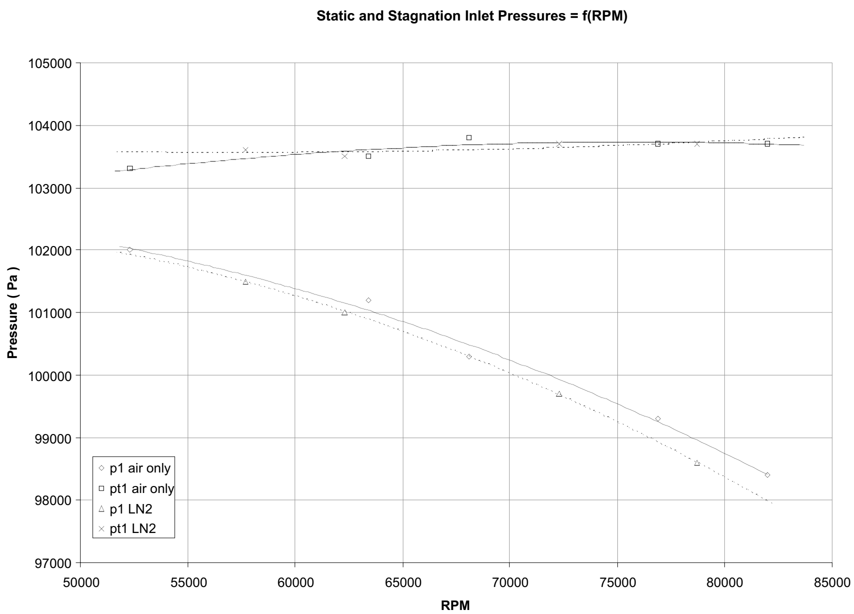

fig.9

Using Castelli's law, one can derive the next relation between the mass flows $\dot{m}'$ and $\dot{m}$:

$$\frac{\dot{m}}{\dot{m}'} = \frac{\rho}{\rho'} \qquad [13]$$

With a constant total pressure, the density ratio becomes quite complex. The following equation, originating from formula 13 is obtained, using the ideal gas law :

$$\left(1 + 0.2M_1^2\right)\left(\frac{\dot{m}}{\dot{m}'}T_1\right)^{2/7} = T_{1'}^{2/7} + 0.2M_1^2 T_1 T_{1'}^{-5/7} \qquad [14]$$

From equation 14, $T_{1'}$ and $T_{t1'}$ can be calculated. The determination of $T_{1'}$ with the method of constant static pressure p_1 is easily obtained using relation 13 and the ideal gas law :

$$\frac{\dot{m}}{\dot{m}'} = \frac{T_{1'}}{T_1} \qquad [15]$$

One can assume that $T_{1'}$ determined by the method of constant stagnation pressure approximates the

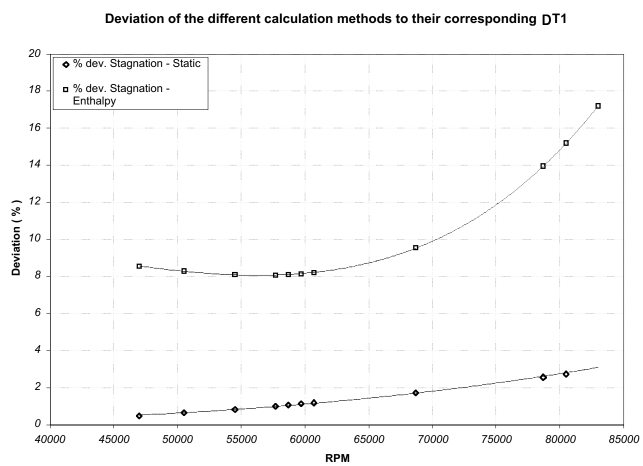

fig. 10

real value of $T_{1'}$ best, because its hypothesis is based on measured data. It should be mentioned that the stagnation temperature drop equals the static temperature drop, since the inlet airspeed is considered to be constant. Now we can obtain an idea of the deviation between the calculated temperature drop ΔT_{t1} originating from the different methods (fig. 10), using measurement data. It is obvious that the deviation between equation 14 and 15 is minor : about 3.5%. As a consequence, the use of formula 15 is justified to calculate the stagnation temperature drop caused by LN2 injection.

4.3 Experiments

In this paragraph, we will discuss the RMA measurement data. This paper will emphasize the influence precooling has on the net thrust T_N and the TSFC. In addition, a new parameter will be created that completes the TSFC : the $TSFC_{N2}$. Also a few words will be said about the icing we had on the compressor blades.

In this paper, most of the data will be used from different run-ups performed at the RMA. This is deliberately done in order to be able to stress some phenomena.

Figure 11 shows the impact of precooling on the inlet temperature at different engine settings. *Note that* $\dot{m}_{N2}$ *remains always constant* for each test, being in this case 0.0105 kg/s. The dotted lines mean extrapolation. Figure 12 gives an overview of the relative increase of nitrogen mass in the inlet air during the same test. One can conclude that no significant changes are made to the composition of the inlet air.

In paragraph 3, there were 4 scenarios introduced. Thanks to the acquired data, they could be verified. They corresponded quite well with reality. Precooling without fuel addition shows no noticeable increase or decrease in thrust. Figures 13 and 14 show the impact of precooling with constant TIT and EGT on the thrust T_N. One can see clearly that a decreasing T_{t1} boosts the thrust. In the case of the SR-30, the thrust increased with more than 140% (fig. 15). Note that precooling with constant EGT causes a larger rise in thrust then a constant TIT tuning.

If we consider the impact precooling has on the TSFC, one can see again its positive influence (fig. 16). The TSFC drop peaks at 35.6% with a constant TIT setting and 49.4% with a constant EGT tuning. Still, comparing TSFC's on the basis of precooling is just not the right thing to do at system (aircraft) level. One has to bear in mind that an additional fluid is injected in the engine, coming from the airplane. Consequently, there is a fluid consumption. This asks for a redefinition of the TSFC :

$$TSFC_{N2} = \frac{\dot{m}_f + \dot{m}_{N2}}{T_N} \qquad [16]$$

Using the same data, the *increase* of $TSFC_{N2}$ peaks at 223.5% with a constant TIT and at 205,3% with a constant EGT. The values of $TSFC_{N2}$ are given in figure 17. It is obvious that the $TSFC_{N2}$ will play a tremendous role in determining the dimensions and weight of the airplane. Using precooling to reduce fuel consumption *seems* to be useless, especially on the SR-30, since we have to inject much more nitrogen than what we gain in fuel.

But, inlet precooling offers also the advantage that to obtain the same thrust, a lower engine regime is required. This means lower centrifugal forces working on the blades, smaller loads on the bearings and less high temperatures ruling in the engine. All of them improve engine life and overhaul time. Additionally, precooling allows the turbojet to fly at higher Mach numbers (2), since it decreases the inlet stagnation temperature, which is favourable for the compressor. Moreover, inlet precooling offers the advantage of delivering a higher thrust with a constant size and volume engine, thus a constant engine mass, allowing to use the same engine in a larger UAV or with a much higher payload.

Vanderlinden (3) compared the theoretical derived thrust and thermal efficiency with the ones obtained during the tests. Concerning thrust, a deviation of -55% and 15% was determined at idle and maximum regime respectively. Regarding the thermal efficiency, an aberration of -60% and -5% at idle and at maximum regime respectively, was found. The reason of the large fluctuations is mainly caused by the losses in the exhaust pipe, which are not taken into account in equation 1 and additional losses due to the compactness of the engine, which are not taken into account either. That will be the subject of further modeling work at RMA.

4.4 Icing

During some tests with precooling, heavy icing on the blades of the compressor was noticed, turning them white (fig.18). The icing, caused by the condensation and freezing of the water vapour in the inlet air, on the compressor blades deformed their shape, causing the efficiency to drop tremendously (fig. 19). Since $\dot{m}_{N2}$ was kept constant, an increase in RPM caused a smaller temperature drop and a higher relative stagnation temperature, causing the ice deposition to decrease. A very important conclusion regarding the icing problem is the following : if we could avoid icing on the compressor blades (and inlet, but this was not the case during the SR-30 tests), higher engine performance could have been obtained and thus a lower TSFC.

CONCLUSIONS

One can conclude that precooling with direct LN2 injection is favourable when a large increase in thrust is required, for instance if an engine with insufficient thrust has to be installed, which can be the case on large UAV or on UAV with high external drag.

If one considers to increase the range of an airplane using this cooling method, there should be taken into account that additional space has to be foreseen on board of the aircraft, which could have been used for fuel storage. Moreover, the $TSFC_{N2}$ rises with precooling, inclining to the idea that direct liquid nitrogen injection is useless for this purpose. Though, when thrust is the only requirement and not range or endurance, precooling can offer a low cost solution.

At high speeds, precooling can also be used to decrease the inlet stagnation temperature, allowing the turbojet to fly at higher Mach numbers, what could be of interest for UCAV applications.

REFERENCES

1. BUYSSCHAERT, F., Experimentele studie van de voorkoeling op een mini-turbojet. K.M.S.-K.H.B.O., August 2001.
2. WALL, R., New Launcher eyed for small satellites, AW&ST, November 5, 2001.
3. VANDERLINDEN, J., Studie van voorkoeling op straalmotoren. K.M.S.-V.U.B., January 2002.

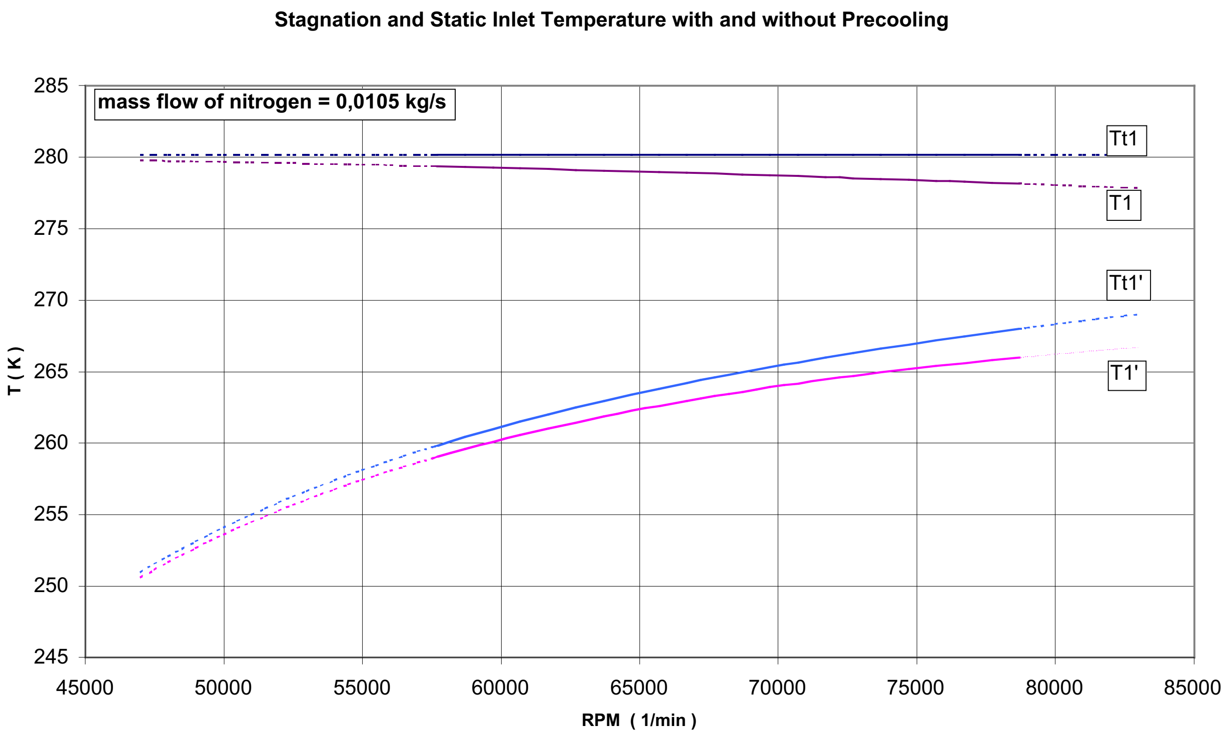
Stagnation and Static Inlet Temperature with and without Precooling
mass flow of nitrogen = 0,0105 kg/s
Tt1
T1
Tt1'
T1'
T (K)
285
280
275
270
265
260
255
250
245
45000
50000
55000
60000
65000
70000
75000
80000
85000
RPM (1/min)

fig. 11

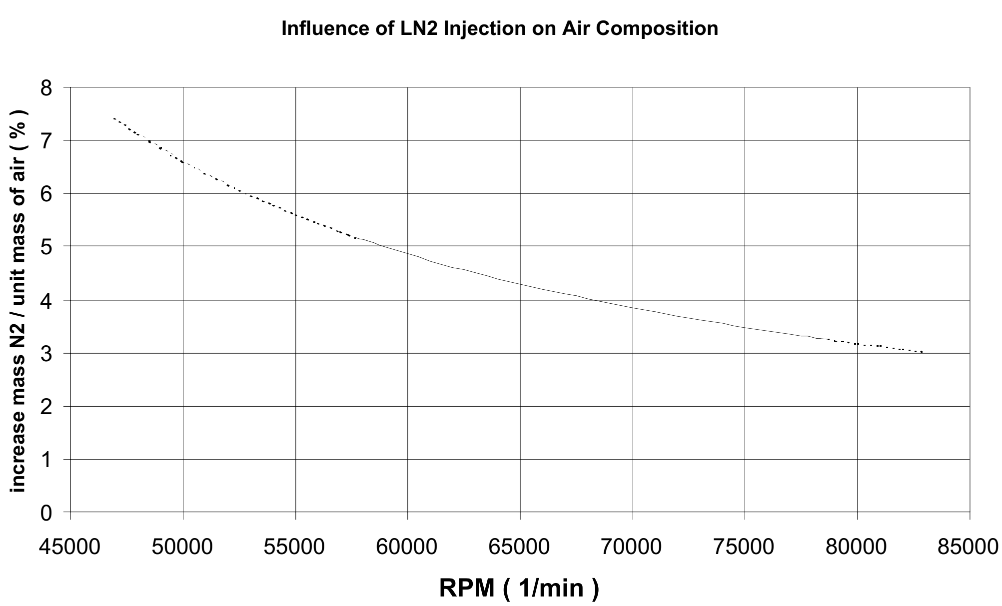
Influence of LN2 Injection on Air Composition
increase mass N2 / unit mass of air (%)
8
7
6
5
4
3
2
1
0
45000
50000
55000
60000
65000
70000
75000
80000
85000
RPM (1/min)

fig. 12

TN = f(EGT,Tt1)

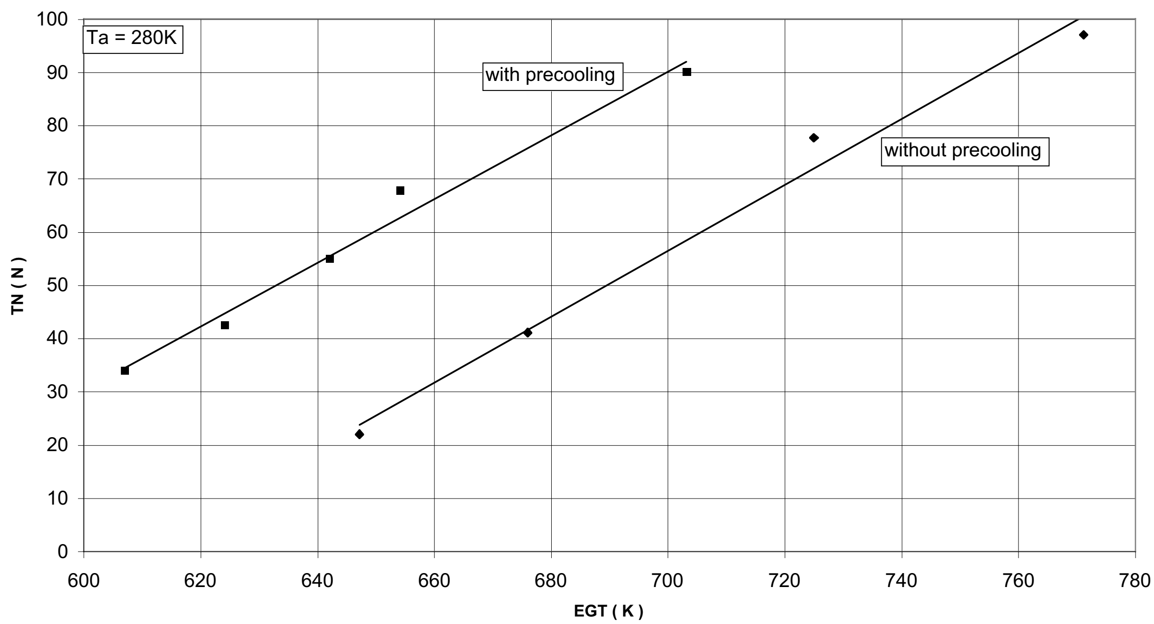

fig.13

TN = f(TIT,Tt1)

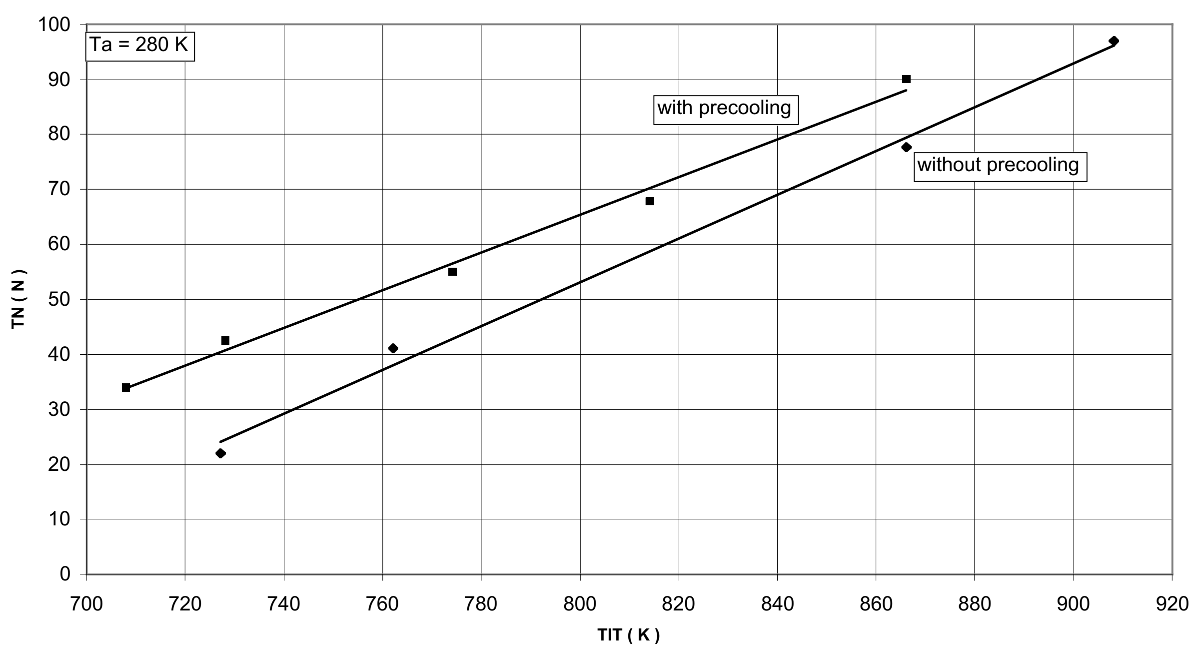

fig. 14

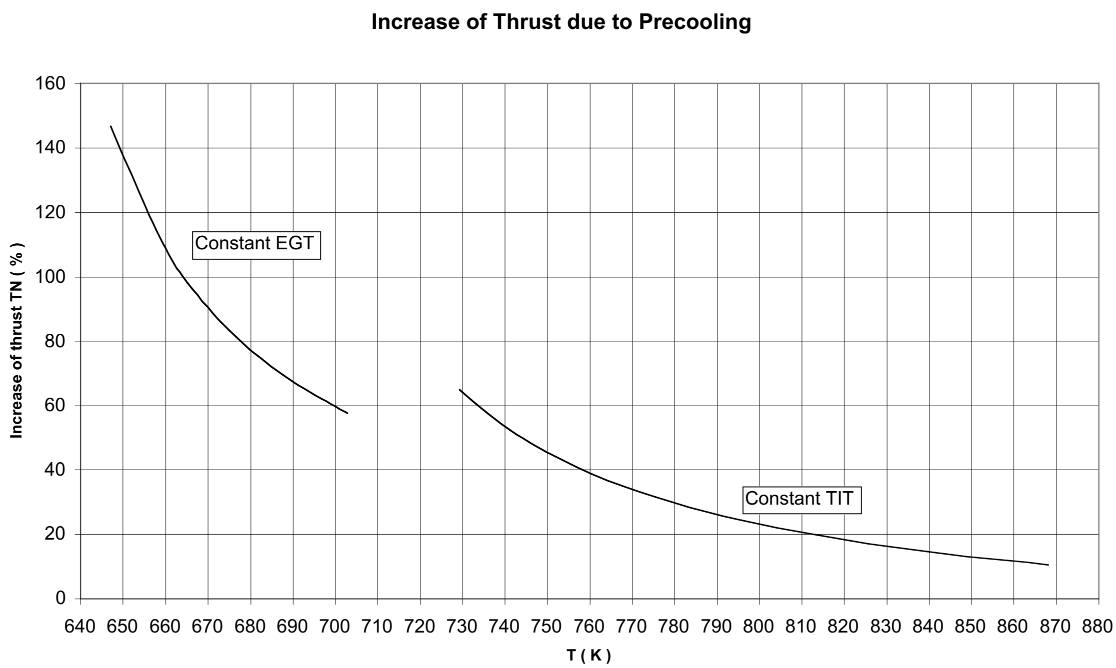
Increase of Thrust due to Precooling
160
140
120
100
80
60
40
20
0
Increase of thrust TN (%)
Constant EGT
Constant TIT
640 650 660 670 680 690 700 710 720 730 740 750 760 770 780 790 800 810 820 830 840 850 860 870 880
T (K)

fig. 15

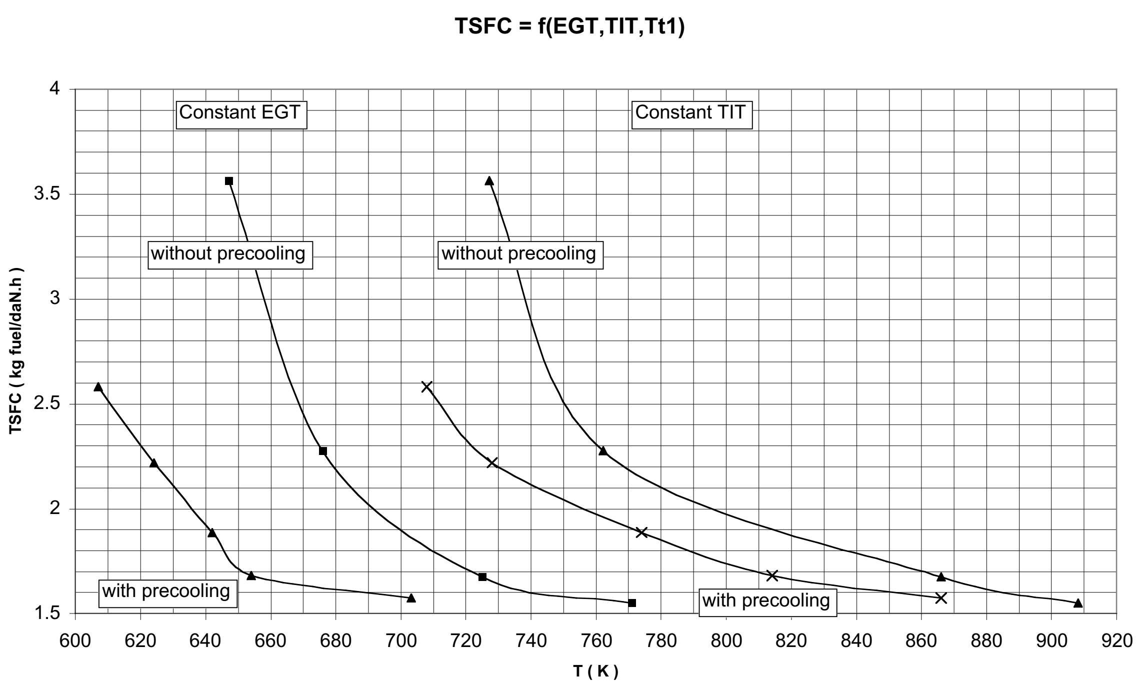
TSFC = f(EGT,TIT,Tt1)
4
3.5
3
2.5
2
1.5
TSFC (kg fuel/daN.h)
Constant EGT
Constant TIT
without precooling
without precooling
with precooling
with precooling
600 620 640 660 680 700 720 740 760 780 800 820 840 860 880 900 920
T (K)

fig. 16

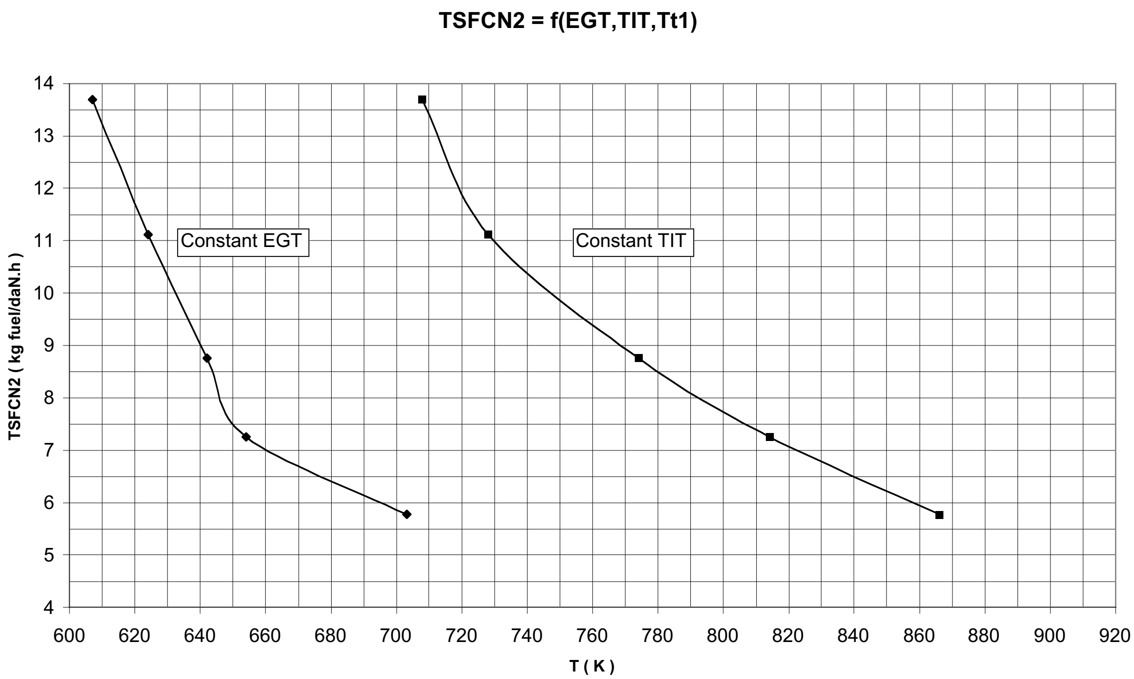
TSFCN2 = f(EGT,TIT,Tt1)
14
13
12
11
10
9
8
7
6
5
4
TSFCN2 (kg fuel/daN.h)
Constant EGT
Constant TIT
600
620
640
660
680
700
720
740
760
780
800
820
840
860
880
900
920
T (K)

fig. 17

fig. 18

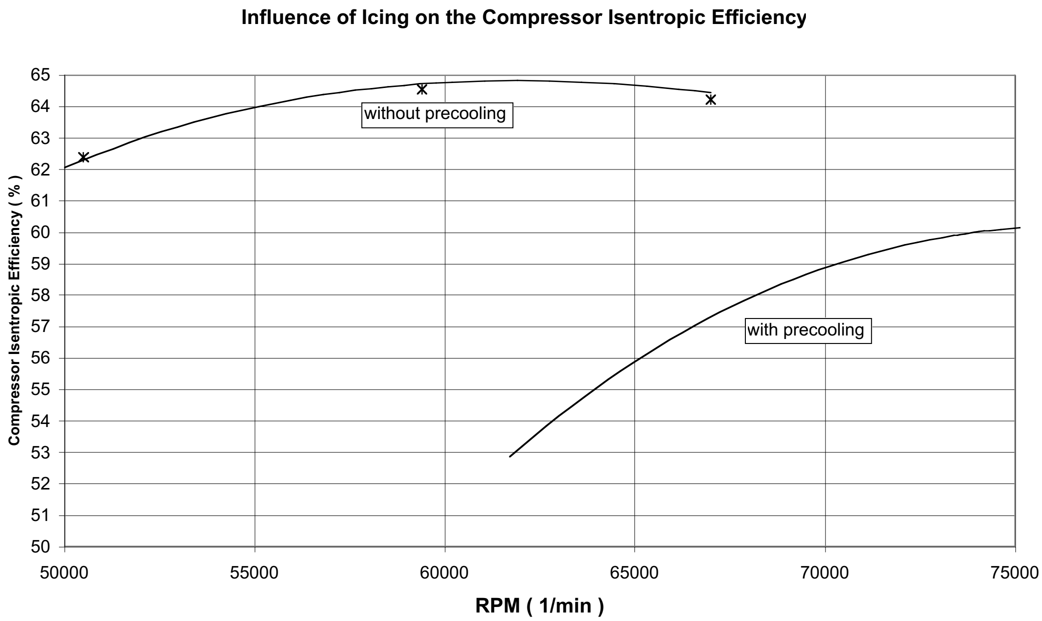
Influence of Icing on the Compressor Isentropic Efficiency
Compressor Isentropic Efficiency (%)
65
64
63
62
61
60
59
58
57
56
55
54
53
52
51
50
50000
55000
60000
65000
70000
75000
RPM (1/min)
without precooling
with precooling

fig. 19