KLIN CYCLE : COMBINED PROPULSION FOR VERTICAL TAKE OFF LAUNCHER

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Abstract

Paper is a progress report on development study of the earlier introduced rocket based combined cycle KLIN including deep cooled turbojet (cryojet) thermally integrated with rocket engine and its application to space vehicle, preferably vertically take-off SSTO and TSTO. The KLIN cycle can be integrated with the vehicle using aero assist lift, for example, of the lifting body shape. Flight scenario for the vehicle with moderate aerodynamic lift force is discussed. New configuration of the DCTJ is shown. Engine performance map and mass data are obtained.

Nomenclature.

C_O^A - oxygen concentration in atmospheric air ;
G - flow rate;
I - specific impulse;
K_A - air cooling ratio (air to total hydrogen ratio in KLIN cycle), analog of the liquefaction ratio for LACE;
K_0 - oxygen/hydrogen stoichiometric ratio;
K_X - LRE equivalence mixture ratio;
L_0 - stoichiometric mixture ratio of the airbreather;
M - mass;
T - temperature;
Q - dynamic pressure;

ε - equivalence mixture ratio;
γ - engine thrust to weight ratio;
η - precooler temperature efficiency;
φ - fraction of the injected oxygen in air+oxygen mixture;
ρ - density;
σ - pressure recovery factor;
ξ - hydrogen distribution factor (ratio of the DCTJ's hydrogen to total hydrogen flow rate through the KLIN cycle);
ψ - LRE throttling factor.

Abbreviations.

DCTJ - deep cooled turbojet;
GTOW - gross take off weight;
LRE - liquid rocket engine;
RBCC - rocket based combined cycle;
SLS - sea level static (conditions);
SSTO - single stage to orbit;
TJ - turbojet.

Introduction

Combined cycle consisting of thermally integrated deep cooled turbojet (DCTJ) and liquid rocket engine (LRE) was initially proposed as alternative to pure rocket propulsion for vertical take off conical rocket of Delta Clipper type, Ref.1. Optimal combination of the engine efficiency (specific impulse) and mass provides the payload fraction benefit of the combined engine powered SSTO rocket on the level of 2.5-2.8% of the vehicle initial mass compared to rocket powered by pure LRE propulsion.

Detachable and recoverable airbreathing booster instead of solid one could also be developed for expandable rockets of H-2 type based on this cycle. In latter case benefit was estimated as high as 2.3 times increase of payload fraction compared to current figures for H-2 rocket.

DCTJ/LRE combined cycle offering wide flexibility in engine efficiency/mass combination, is also suitable for boost-glide vehicle requiring lightweight efficient propulsion system for high ascent and than unpowered glide, nonsustained flight.

DCTJ/LRE cycle falls under definition of combined cycles given by Dr. Escher[2]: "Combined-cycle propulsion system are single, fully integrated engines, generally of new design, that are capable of multimode operation over a wider speed range than

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conventional airbreathers. Operating mode include airbreathing (transatmospheric), rocket (space), and mixed airbreathing/rocket (takeoff, initial acceleration)".

This cycle could be considered as rocket-based combined cycle (RBCC) because primary rocket subsystem starts at sea-level static conditions, Ref.2. The main feature of this subclass - thermal integration of rocket engine and air processing units - significantly change airbreathing cycles in terms of performance, materials and mass. This change leads to possibility of beneficial compromise between engine performance and mass that makes reasonable and attractive application of mentioned cycles to **vertical take off** rockets. Being heavier than pure rocket engines of equivalent thrust, in case of vertical take off application considering cycle does not require added vehicle thermal protection for atmospheric ascent, allows to eliminate trolley and wings (reasonable lifting force to be provided by vehicle body), causes only a small increase of propellant tank volume compared to pure rocket system.

According to Dr. Hunt[7], an airbreathing/rocket SSTO vehicle design is rich in variables and can evolve to a robust flexible machine through a highly optimized design process if systems/disciplines are integrated synergistically and the appropriate technologies matured.

Proposed combine cycle offers very flexible characteristics and unique compromise between cycle mass and fuel efficiency and it is fully within **near term** industrial capability. Available technologies and possibility to be demonstrated within existing **ground test** facilities[8] are significant advantages allowing to minimize development risk and cost.

One of the main assumptions for the DCTJ/LRE powered vehicle considered in Refs.1, 3, 4 was, that thrust to weight ratio is always above unity and aero assist is not used during ascent. In order to provide more flexibility and oxygen saving by reasonable control of the combined cycle, vehicle shape providing **moderate lifting force** can be chosen. Flight path should be selected in such manner that the vehicle does not require added thermal protection for atmospheric ascent compared to re-entry regime. Configuration of the proposed cycle can be integrated with aero-assisted lift combined with the use of such features as an aerospike nozzle, yielding both major aerothermodynamic and structure advantages, with appropriate trajectory optimization.

In current study, initial data base of the DCTJ/LRE performance and mass was obtained. Paper gives some examples of the major parameters, describes key features of combined cycle operation, introduces complitely renewed dimensional scheme of the DCTJ with breif structure description. Integrated DCTJ/LRE propulsion system was named KLIN cycle in Ref.3 (KLIN means *wedge* in Russian).

General description of the integrated DCTJ/LRE propulsion system.

Scheme of DCTJ/LRE thermal integration is shown in fig.1. Thermal integration of TJ and LRE means use of the cooling capacity of the hydrogen of LRE along with TJ's own hydrogen for deep air precooling in TJ. Use of "two hydrogens" allows deep cooling the amount of air enough for near stoichiometric operation of TJ and leads to high performance of propulsion system at relatively small mass.

In fact, **DCTJ is not just TJ equipped by precooler**. Airbreathing cycle is changed significantly in terms of performance and mass. Following savings contributes in total mass saving:

- heat exchanger has no "pinch point" like cooler-condenser in LACE cycle that has minimal temperature difference between air and hydrogen coolant on the level of 10-15K. Fig.2 shows comparison of the relative mass of cooling systems of LACE (without condenser) and KLIN cycle made at the same assumptions. It is seen that even without means of air liquefaction (condenser, compressor, slush circulation, para-ortho conversion), cooling system of LACE cycle is 5-10 times (depending on air to hydrogen ratio) heavier than that of DCTJ/LRE cycle;
- compressor mass reduction compared to non-precooled turbomachinery by two reasons : 1) because of significant reduction of total work at deep air cooling - by 2.4-2.9 times depending on air temperature compared to non precooled engine with the same pressure ratio; 2) structure could be made of light weight carbon fiber reinforced plastics ($\rho \cong 2000$ kg/m^3) or aluminum alloys ($\rho \cong 2700$ kg/m^3). It was found that temperature of the air behind compressor in all regimes for engine with sea level pressure ratio π_c=30 is not higher than 400-450K, Ref.3;
- turbine and shaft mass reduction because of decrease of required work and proportional decrease of loadings.

Low pressure hydrogen (DCTJ fuel) after precooler passes in TJ combustor and afterburner (fig.1). High pressure hydrogen after precooler (LRE fuel) is used for to LRE combustor cooling. Such configuration of the KLIN cycle arises two main questions: 1) is hydrogen cooling capacity enough for rocket combustor cooling after precooler at high Mach number; 2) is it possible to use high pressure hydrogen (p=270+ bar) in the precooler installed in the air duct from the point of view of reliability. Possibilities to eliminate high pressure hydrogen use in the precooler located in the air duct are currently under study.

In Ref.4 oxygen augmented DCTJ was considered. Subcooled LOX was proposed to inject in front of precooler. **The main objective** of oxygen injection at low flight altitude is to reduce air temperature in front of precooler below water triple point. According to Refs. 1 and 4, no precooler icing is expected at air stagnation temperature in front of precooler T_a^{in} below 273K and at steam partial pressure Pst below steam pressure in the triple point Ptr (Ptr =0.00623 atm). This two conditions define seasonal speed-altitude limits of icing. These limits were estimated for the conditions of north-east Hokkaido in Japan. This place is candidate for the launch site in ATREX flight testing program, Ref.5.

According to estimations, no icing is expected in November-April period mainly because of average partial steam pressure in this period is lower than water triple point pressure. Icing-free operation in this period was proven by precooled ATREX ground test, Ref. 5 and 6.

In the most humid season - July, August - icing limits are to be reached at the altitude about 4km at Mach≈0.8, Ref.4. It was assumed for KLIN cycle simulation that oxygen is injected into the airflow in front of precooler from SLS to Mach≈0.8.

4% oxygen addition is adequate to chill standard air at 288K to below water triple point assuming that the injected oxygen is at 55K.

Another serious advantage of oxygen augmentation is DCTJ thrust increase with almost no changes in precooler and compressor hardware. Thus, oxygen injection in the amount of 10% of air flow leads to thrust increase by more than 20%. About half of that is contributed by flow rate increase, and another 10% - by exhaust velocity increase because of higher combustion temperature.

Advantages of the KLIN cycle could be summarized as follows:

- simple configuration : such ideas as oxygen or helium closed loop use for additional air cooling, or application of the bypass turbojet as airbreather were rejected from the beginning of concept analysis in order to have simple design;
- near term technology. Reliable precooler is, probably, the most advanced unit;
- light weight structure because of high efficiency of air processing (high specific thrust), 'excess' of cooling hydrogen and low temperature compact compressor;
- high engine thrust to weight ratio ;
- two-three times higher specific impulse than for LRE;
- known solution for icing problem.

Main parameters of the scheme defining performance and mass of the propulsion system are : the ratio of the air flow rate and total (LRE fuel and TJ fuel) hydrogen flow rate K_A, factor of hydrogen distribution between TJ and LRE which is the ratio of TJ's hydrogen and total hydrogen flow rate - $\xi = G_H^{TJ}/G_H^{\Sigma}$, and fraction of the injected oxygen in air+oxygen mixture $\varphi = G_{OX}/(G_A + G_{OX})$. Listed parameters define equivalence mixture ratio as

$$\varepsilon = \frac{\xi L_0(1-\varphi)}{K_A} \tag{1}$$

where $L_0 = \dfrac{K_0(1-\varphi)}{C_O^A + \varphi(1-C_O^A)}$ - stoichiometric ratio of air+oxygen mixture to hydrogen.

Total specific impulse of the integrated propulsion system is

$$I_\Sigma = \frac{(1-\xi)(K_X+1)I_{LRE} + K_A(W_g - V_f) + \xi(1-\varphi)W_g}{1+\varphi(K_A-1)+(1-\xi)(1-\varphi)K_X} \tag{2}$$

where I_{LRE} - LRE specific impulse; W_g - exhaust velocity of DCTJ; V_f - speed of flight.

Fraction of TJ thrust in total thrust at sea level conditions is

$$\bar{R}_{TJ} = \frac{1}{\dfrac{(1-\xi)(K_X+1)(1-\varphi)}{K_A+\xi(1-\varphi)}\dfrac{I_{LRE}}{W_g}+1} \tag{3}$$

The second important parameter along with specific impulse is propulsion system specific mass which is engine mass to thrust ratio

$$\gamma_\Sigma = \frac{\gamma_{LRE}}{\psi}(1-\bar{R}_{TJ}) + \frac{\bar{M}_{TJ}^a(1-\varphi)}{I_\Sigma\left[1+\varphi(K_A-1)+(1-\xi)(1-\varphi)K_X\right]} \tag{4}$$

where γ_{LRE} - specific mass of the LRE; $\bar{M}_{TJ}^a$ - mass of the TJ per 1kg/sec of airflow; ψ - LRE throttling factor.

Mass of the TJ includes: air intake, precooler, turbomachinery, and nozzle mass.

Main assumptions and selected flight scenario.

Main assumptions of current study are as follows:

1. The vehicle is currently intended for vertical take off operation (this assumption defines some thrust profile limitations);
2. Different trajectories with constant dynamic pressure in the range of Q=30000-60000 Pa was considered at Mach>1.2. For lower Mach number some common transition trajectory was used.

3. Combined cycle includes throttlable LRE of LE-7 type with vacuum specific impulse I_{SP}=4372 m/s, and specific mass γ_{LRE} =18kg/ton. Variation of the number of operating LREs could be used instead of throttling. For example, use of 2 engines of cluster of 3 is equivalent of 67% throttling.
4. Hydrogen distribution factor ξ was set constant along the trajectory. This condition corresponds to increase of total equivalence mixture ratio of DCTJ in the condition of decreasing air flow.
5. Take off thrust to weight ratio of the vehicle was taken as 1.3.
6. Design point of precooler corresponds to sea level static conditions. Initial air temperature behind compressor T_a=110K, initial pressure recovery factors : for air intake σ_{in}=0.95, for precooler σ_{pc}=0.85.
7. Compressor pressure ratio at SLS conditions was taken as π_c=30. It was assumed that low total compression work allows single spool compressor.
8. Compressor and turbine efficiency were assumed as η=0.82.
9. Carbon fiber reinforced plastic (ρ=2000 kg/m^3) was assumed as material for compressor rotor and stator and also for precooler shell.
10. 'Baraban' type[5, 6] precooler was selected. Stainless steel tubes of 3mm outer diameter with wall thickness 0.1mm was considered.
11. Subcooled liquid oxygen at 55K is injected in front of precooler from SLS static conditions till Mach≈0.8 and altitude H≈3.6 km in order to prevent precooler icing and to increase DCTJ thrust.
12. Combustion of the triple mixture - air, oxygen, and hydrogen - was considered at 96% exhaust efficiency.

As it was mentioned, in previous studies of combined cycle, DCTJ and LRE simultaneous operation from starting conditions till Mach=6.0 was considered. Number of engines, thrust distribution between airbreather and rocket engine was selected based on two assumptions - initial thrust to weight ratio of the vehicle is 1.3, thrust to weight ratio of the vehicle in the initial moment after DCTJ cut off (transition on pure rocket mode) equal to unity.

In order to increase oxygen saving, in current study regime of **LRE cut off after initial acceleration** is considered. In general, fligth scenario consists of four rather different operational modes shown in fig.3 as a profile of the vehicle thrust to weight ratio (Similar dimensional picture is given in fig.8).

Mode 1 (from take off till Mach ≈ 0.8) corresponds to simultaneous operation of all DCTJ units with oxygen augmentation and all or part of LRE units (LREs could be also throttled). Maximum absolute thrust necessary for vertical take off and moderate specific impulse are produced. Oxygen injection in front of precooler protects device of icing and provides more than 20% of DCTJ thrust increase with the same hardware.

Mode 2 (in the range of Mach≈0.8-1.2) begins after oxygen injection cut off. Initially thrust decreases along with specific impulse increase. Than thrust is gradually recovered.

Mode 3 (in the range of Mach≈1.2-6.0) begins with LREs cut off. Only DCTJ units operate in this mode. Thrust decreases dramatically (initial level is proportional to the final value of the $\overline{R}_{TJ}$ on mode 2 -see Eq.3), specific impulse reaches its highest value in this mode. According to assumption, hydrogen flow rate remains constant in order to provide air deep cooling. During acceleration thrust continues to decrease, aero assist is required for ascent. By the end of this mode thrust to weight ratio of the vehicle is significantly below unity. Level of admissible thrust to weight ratio could not be defined without vehicle analysis. In current study minimum at Mach=6.0 value was admitted as low as ≈0.5.

Mode 4 (from Mach=6.0 to orbital speed) - pure rocket mode, begins after DCTJ cut off and LRE switch on. Use of lifting force is not necessary any more. Condition of the vehicle thrust to weight ratio equal to unity was assumed for the beginning of mode 4. In general, number of operating LRE units in modes 1-2 and 4 could be different, LRE units could also be throttled in modes 1-2.

Cycle fuel efficiency is as always in conflict with engine mass. It should be noted that the main task of low speed modes 1 and 2 is to provide **lowest engine weight to thrust ratio** even at the cost of the cycle efficiency. Main task of the mode with more extensive use of the lifting force (Mode 3) is to provide high specific impulse and significant on-board **oxygen saving**.

It should be noted that in previously considered concept, Ref.1 and 2, three of mentioned modes was employed -1, 2 and 4. Vehicle thrust loading was always above unity that causes moderate specific impulse. Thrust profile for reference concept is shown in fig.3 by dotted curve.

Matching airflow through the system 'air intake-precooler-compressor'

Turbomachinery based airbreathing engines with wide range of operation Mach number are rather complicated objects to control. In case of KLIN cycle, operation of air intake, precooler, turbomachinery and nozzle should be matched in terms of flow rate capacity in all regimes. Current study presents the first attempt of airflow matching for precooled turbomachinery with high pressure ratio.

It was shown in Ref.3 that turbojets of the KLIN cluster could be gradually cut off during acceleration if sufficient air flow could not be provided. In current study, trajectories with higher dynamic pressure were explored, besides, compressor map was assumed wide enough (relative corrected air flow $\overline{G}_{corr}$=0.5 - 1.1), therefore, operation of the same number of DCTJ unuts from take off to Mach=4.0 was assumed and issue of the single TJ control at higher Mach number is not discussing here.

Air flow through airbreathing propulsion system is defined by the unit with lowest air flow rate capacity on the considering regime. For KLIN cycle precooled turbomachinery, sea level static conditions were choosen as design point because of the highest thrust demand.

Design point for air intake could be selected in wide range of Mach number within airbreathing mode. Practical restrictions are: at low design Mach number - rapid decrease of the air flow at higher Mach numbers, at high design Mach number - too heavy air intake. In current study Mach=4.0 was selected as air intake design point. At higher Mach number air intake is the unit restricting air flow through the airbreather. At lower Mach number precooler and turbomachinery restrict air flow.

Fig.4 shows precooler map in the form of lines of the equal flight Mach number in the space of relative air flow (current air flow devided by air flow for design point) and air temperature. Hydrogen temperature at the precooler inlet was assumed as T_h=26K.

Characteristics of the compressor were defined using generalized map of high pressure compressor under the condition of constant pressure behind compressor till Mach =4.0. This condition gives the level of compressor pressure ratio for different Mach numbers and corresponding values of the corrected air flow. Actual air flow at certain Mach number is defined from simultaneous consideration of the precooler and compressor maps. When flight Mach number is higher than that for air intake design point, air flow capacity of the airbreather is defined by air intake.

Fig.5 shows combined perfomances of **precooler** and **compressor** for Mach ≤4.0 and combined performance of **air intake** and **precooler** at Mach>4.0 for different values of the flight dynamic pressure. Therefore, all the lines of combined performance have point of inflection on the line of Mach=4.0.

These data on air flow and air temperature in front of compressor were used for KLIN cycle performance evaluation. Dotted line in fig.5 shows air flow characteristic for the cycle considered in Ref.3, where design point for air intake on the level of Mach=2.5 was selected in order to have lighter engine.

Fig.6 gives the map of air flow performance as a function of flight Mach number. Data for the cycle considered in Ref.3 are also shown by dotted line.

KLIN cycle performance. Example of the vehicle sizing.

Simulation were made for 4 levels of dynamic pressure inthe range of Q=30000 - 60000 Pa. However, from take off (Mach=0) till Mach=1.22 common trajectory was considered.

For each level of dynamic pressure, 7 levels of the initial air cooling ratio in the range of K_A=8-20 were considered.

One of the key parameter of the KLIN cycle - hydrogen distribution factor, defining DCTJ thrust fraction in total thrust and equivalence mixture ratio, was fixed on the expected to be near optimal level of ξ=0.5 because of uncertain limit of final thrust of DCTJ at Mach=6.0.

Fraction of injected oxygen was also fixed on the level of 10% of the air flow. This parameter does not affect global vehicle efficiency very much, and some excess compared to necessary 4-6% for icing prevention was taken in order to reduce engine specific mass.

Hydrogen flow through propulsion system from take off to Mach=6.0 is constant, despite on LRE cut off at Mach=1.22. This provides very comfortable thermal conditions for precooler and compressor operation because air flow decreases dramatically.

Sample graphs in fig.7 provide major trends for selected cases of Q=50000 Pa, and K_A=8-20.

Fig. 7a depicts change of the vehicle thrust to weight ratio. It should be noted that this parameter depends on vehicle configuration and charactiristics. Analysis of these characteristics is out of the scope of current study. However, this is rather important parameter and its indicative value estimated with aerodynamic characteristics of the previously considered concept is included in estimations.

Thrust to weight ratio of the vehicle in fig.7a changes in accordance with selected flight scenario. After vertical take off with initial value 1.3, thrust to weight ratio increases because of thrust increase with altitude and substantial vehicle mass reduction. Than, after oxygen augmentation cut off, it falls again, and than increases till LRE cut off at Mach=1.22. On airbreathing mode thrust to weight ratio of the vehicle gradually decreases because of inlet air impulse increase with the flight speed and gradual reduction of the air flow. It reaches the level of 0.4-0.5 at Mach=6.0. Study of the vehicle powered by KLIN cycle will answer the question whether this level of thrust to weight ratio enough or not for high flight Mach number.

Initially equal to unity, thrust to weight ratio on the pure rocket mode rapidly increases in further acceleration and lifting force is no longer necessary for the climb.

Specific impulse of the cycle, fig.7b, is changed significantly depending on mode and flight Mach number. Providing moderate advantages on initial acceleration mode, higher air cooling ratio regimes offer much higher specific impulse on pure airbreathing mode. Initially, specific impulse of the combined cycle is seriously affected by simultaneously operating LRE and especially by LOX injection in front of precooler. In the beginning of the pure airbreathing mode specific impulse of the KLIN cycle is almost proportional to air cooling ratio.

Fig.7c depicts change of the relative vehicle mass along the trajectory. Like vehicle thrust to weight ratio, vehicle relative mass is also indicative parameter. Relative vehicle mass is integral parameter and reflects overall vehicle efficiency. Mass saving at Mach=6.0 for the vehicle powered by KLIN cycle with initial air cooling ratio K_A=20, is about 9% of the vehicle initial mass compared to the vehicle powered by KLIN cycle with initial air cooling ratio K_A=8. It could be noted that for previously considered concept of the vehicle (no LRE cut off or throttling, conical rocket, cycle with initial air cooling ratio K_A=8, ξ=0.5) relative mass at Mach=6.0 was by 11% lower than that in current study for the vehicle with KLIN cycle. For the pure rocket it was 25% lower (percents reflect vehicle initial mass).

Fig.7d shows fraction of the DCTJ thrust in total KLIN cycle thrust. Relation of this fraction with cycle parameters is given by Eq.3. The higher air cooling ratio, the higher thrust fraction of airbreather. At Mach=1.22 DCTJ becomes the only thruster till Mach=6.0 and DCTJ thrust fraction becomes equal to unity.

Fig.7e gives the profile of total equivalence mixture ratio of the DCTJ. On oxygen augmented mode, combustion of the triple air-oxygen-hydrogen mixture was evaluated, with corresponding equivalence mixture ratio. As it is seen in fig.7e, in pure airbreathing mode DCTJ is significantly overfueled at all considered air cooling ratios.

Simulation results corresponding to trajectory with dynamic pressure Q=50000Pa and initial air cooling ratio K_A=16 were selected for dimensional example. Table1 and fig.8 give the main parameter for the vehicle with gross take off mass 240 ton. It should be noted that Table 1 provides approximate values because rounded figures of gross take off mass and some other parameters was taken.

Fig.8 shows profile of the major parameters for selected example. Note that in considering example, thrust become lower than mass only after Mach=3.0 (fig.8b).

Table 1. Example of the vehicle sizing.

Gross take off weight, ton	240
Total take off thrust, ton	312
LRE initial thrust, ton	85
DCTJ total initial thrst, ton	227
LRE throttling ratio	0.5
Number of LREs	2x85 ton
Number of DCTJs	6x37.8 ton
Total LRE mass, kg	3060 (2x1530)
Total DCTJ mass, kg	11720 (6x1953)
Initial air flow rate, kg/s	1116 (6x186)
Initial oxygen flow rate, kg/s	209/123 (LRE/DCTJ)
Total hydrogen flow rate, kg/s	69.8

Configuration of DCTJ. Engine weight estimation

KLIN cycle consists of LRE and DCTJ. Existing LRE was selected for estimation. Its specific mass was assumed as 18 kg/ton, although it could be changed with engine design modification, for example, when aerospike nozzle will be used.

DCTJ configuration was estimated aerodynamically, and special mass analysis of major units was done based on statistic data on TJs mass and design evaluation.

Fig.9 gives new configuration of DCTJ drawn in current study and air temperature and pressure parameters in the main stations listed below.

1. LOX injection system provides injection of the liquid oxygen subcooled to 55K. It chills down air to about 240K and freezes out moisture from the air in order to prevent precooler icing.
2. Then air passes through precooler and is chilled down to 110K with pressure recovery factor 0.85.
3. 4-stage compressor increases air pressure by 30 times at design point in SLS conditions. Air is heated up in compressor at design point to 350K. Along the trajectory pressure ratio significantly decreases. Maximum temperature behind compressor is expected within 450K.
4. In DCTJ combustor fuel lean combustion takes place at maximum temperature T=1700K. Hydrogen flow through combustor is variable depending on air flow and oxygen concentration in the air flow.
5. In afterburner combustion of the mixture is completed by adding the rest of hydrogen. For the LOX augmented engine mainly fuel lean combustion

takes place in afterburner at SLS conditions. Maximum temperature in afterburner at SLS conditions was estimated as 2300-2700K (latter figure for fuel rich conditions). These figures show that regenerative cooling of the afterburner is required. However, this question could be discussed in details after the optimal cycle selection.
6. Combustion products expands in DCTJ nozzle. It also could be integrated with the vehicle afterbody, for example, as aerospike type nozzle.

Mass of the following units of the DCTJ were estimated : air intake, precooler, turbojet group, including compressor, turbine, afterburner and nozzle.
Table 2 gives mass breakdown for reference DCTJ including elements of turbomachinery.

Table 2. Mass breakdown of the DCTJ with air cooling ratio K_A=16.

Unit	Fraction in total mass, %
Air intake	28
Precooler	36
Compressor	7
Turbine	10
Afterburner	11
Nozzle	5
Others	3

Fig. 10 gives the trend of KLIN cycle mass as a function of trajectory and air cooling ratio. Nearly twofold increase of the engine mass with cooling ratio increase from 8 to 20 is explained by increase of the precooler mass.

Concluding remarks

KLIN cycle is lightweight near term technology RBCC with beneficial specific impulse for (preferably) vertical take off launchers particularly of lifting body shape.

Oxygen saving up to 30-35% of the vehicle GTOW compared to pure rocket system could be provided by KLIN cycle with temporary LRE cut off in the Mach range 1.2-6.0.

Performance map (air flow and thrust profile, specific impulse) of the integrated oxygen augmented DCTJ/LRE (KLIN cycle) in the range of Mach=0-6.0 is obtained for different trajectories and initial air cooling ratios K_A (analog of the LACE air liquefaction ratio). Mass evaluation of the KLIN cycle in wide range of K_A =8 -20 is conducted.

New configuration of the DCTJ is designed with principal dimensions evaluation (precooler size, compressor and turbine diameters and length, size of the afterburner).

KLIN cycle offers very flexible characteristics and unique compromise between cycle mass and fuel efficiency. Full advantage of the cycle application could be shown in the vehicle analysis. Evaluation of the cycle application to lifting body vehicle, experimental prove of the icing prevention technology, development of the subscaled demonstrator of the KLIN cycle are in agenda.

Acknowlegement.

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Reference.

1. V. Balepin, E. Folomeev, S. Galkin, and E. Tjurikov. "Rocket Based Combined Cycle for Vertical Take-off Space Vehicles", AIAA-95-6078, 1995.
2. Escher, W.J.D., "A Winning Combination for Tommorow's Spaceliners," *Aerospace America*, Feb 1996.
3. V. Balepin, M. Maita, S.N.B. Murthy. "Third way of Development of SSTO Propulsion", AIAA-96-4495, 1996.
4. V. Balepin, M. Maita, N. Tanatsugu, and S.N.B. Murthy. " Deep Cooled Turbojet Augmented with Oxygen for an SSTO Launch Vehicle", AIAA-96-3036, 1996.
5. N. Tanatsugu, V. Balepin, T. Sato, T. Mizutani, K. Hamabe, J. Tomike. "ATREX Engine Development: First Practical Experience of Precooled Turbomachinery", Proceedings of the 5th AAAF Intl. Symp. Propulsion in Space Transportation, pp. 19.25-19.29, 1996.
6. N. Tanatsugu et al. "Development Study of ATREX Engine", AIAA-96-4552.
7. J.L. Hunt. "Airbreathing/Rocket Single-Stage-to-Orbit Design Matrix", AIAA 95-6011.
8. V. Balepin, J. Cipriano, and M. Berthus. "Combined Propulsion for SSTO Rocket : from Conceptual Study to Demonstrator of Deep Cooled Turbojet", AIAA-96-4497.

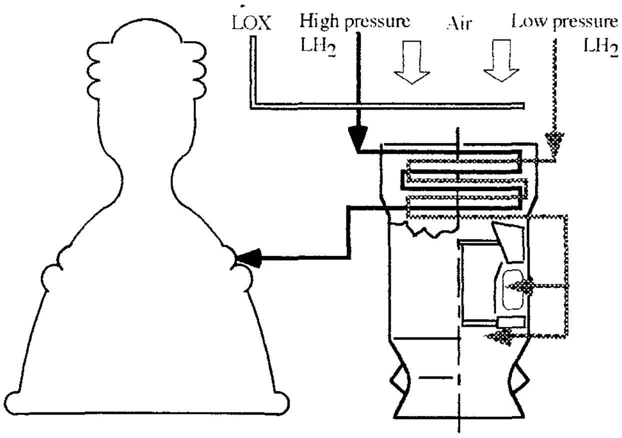


Fig.1 Schematic of DCTJ and LRE thermal integration.

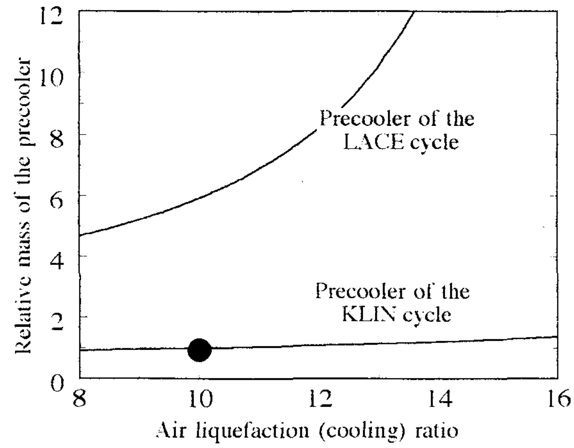


Fig.2 Comparison of the mass of precoolers of the LACE and KLIN cycles evaluated with the same assumptions. Mass of the KLIN cycle precooler at cooling ratio $K_A = 10$ is taken as 100%.

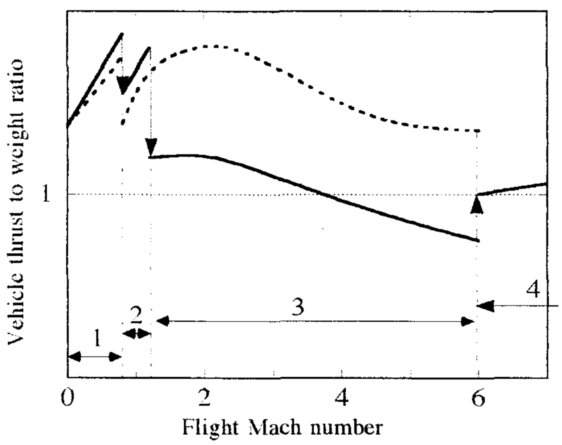


Fig.3 Flight scenario (profile of thrust to weight ratio) for the vehicle powered by KLIN cycle.

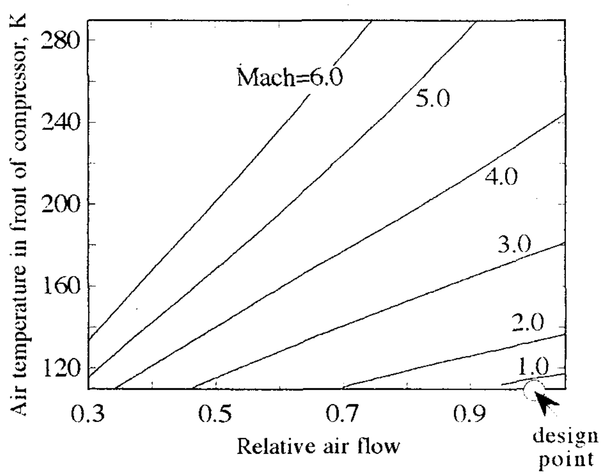


Fig.4 Precooler map.

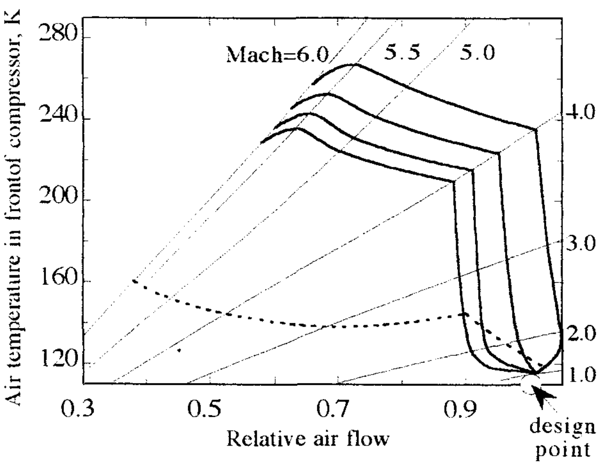


Fig.5 Combined map of the system 'air intake-precooler-compressor'.

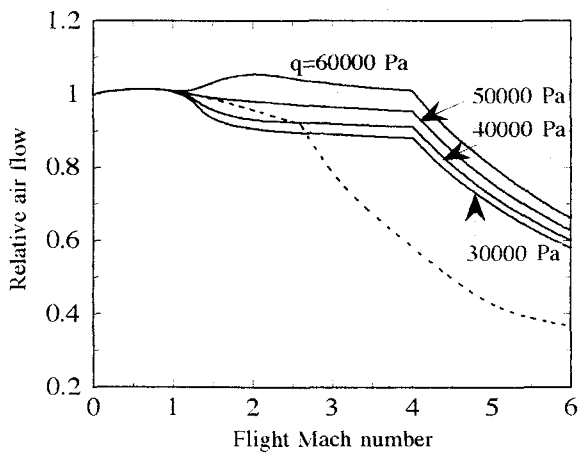


Fig.6 Relative air flow versus flight Mach number for different trajectories.

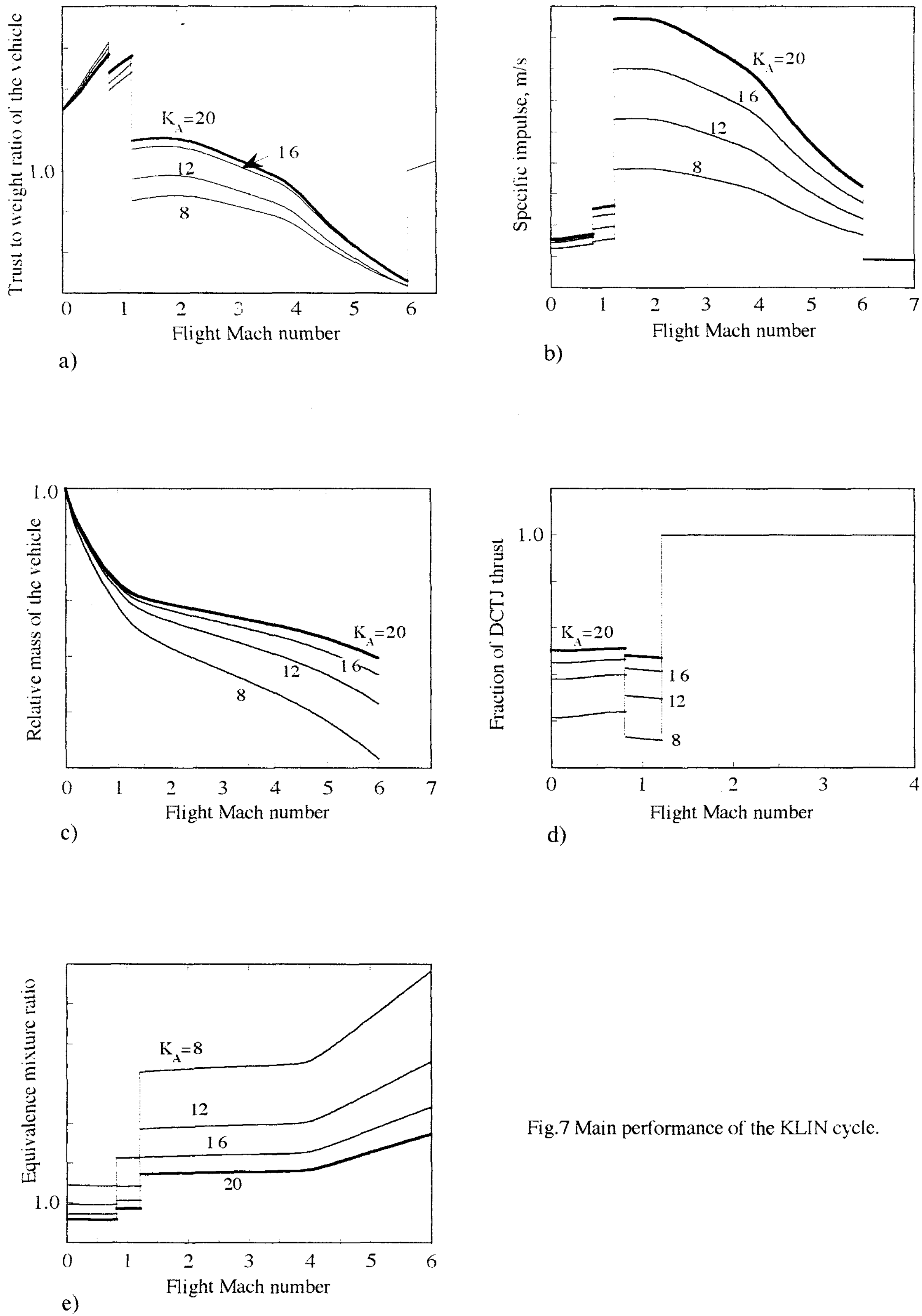


Fig.7 Main performance of the KLIN cycle.

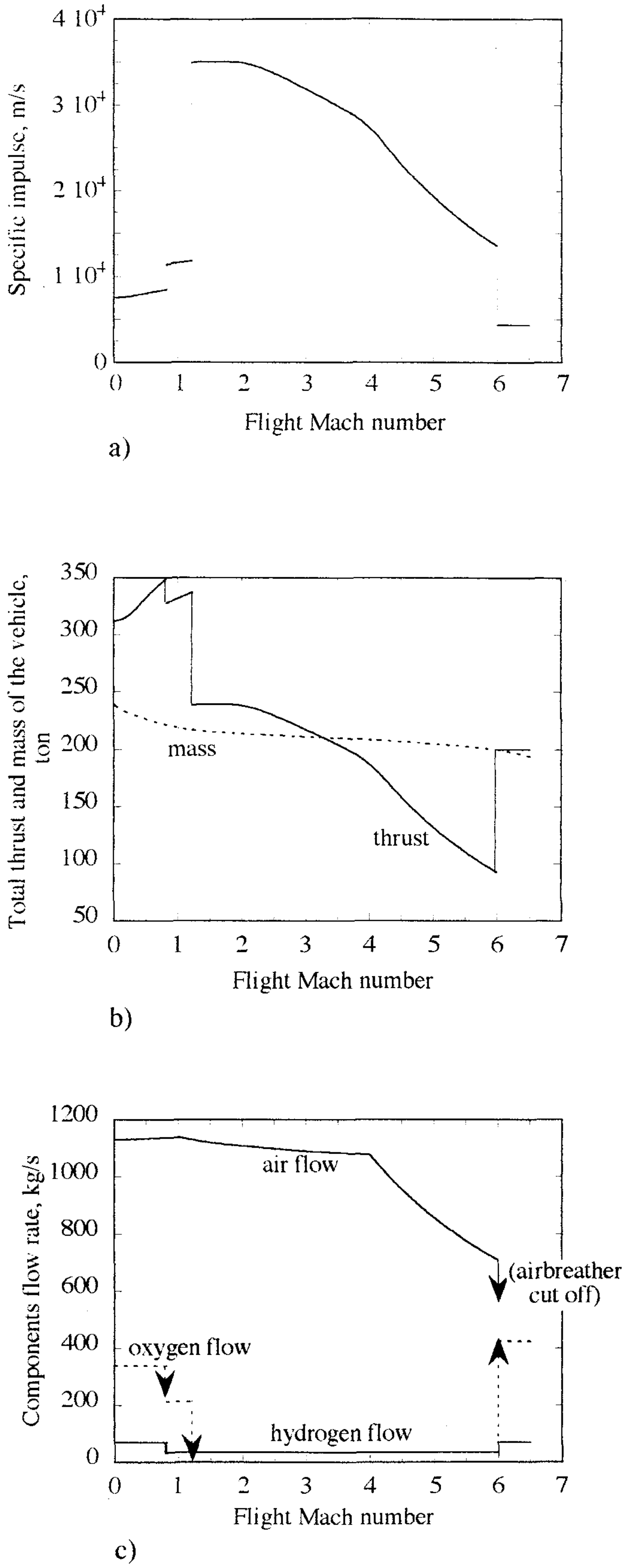
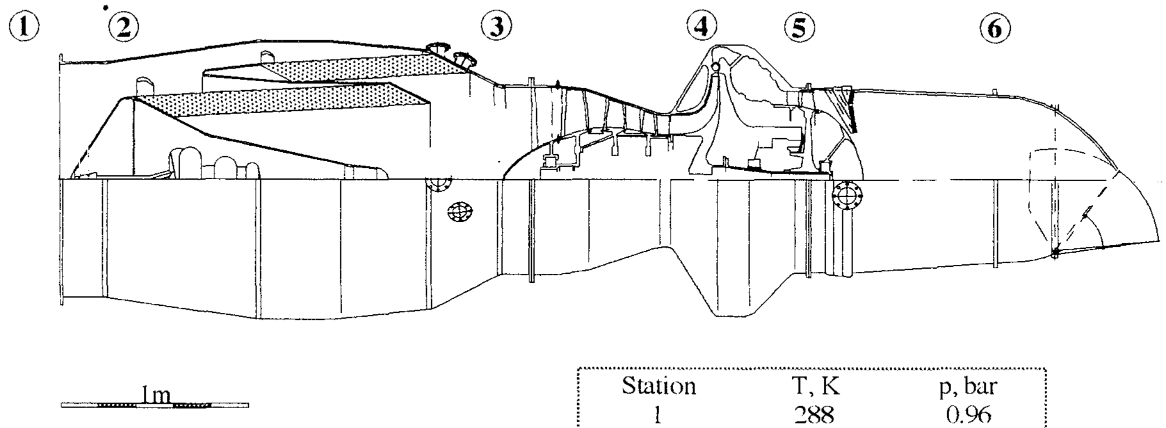


Fig.8 Example of the dimensional KLIN cycle parameters. Q=50000 Pa, $K_A=16$.



Station	T, K	p, bar
1	288	0.96
2	240	0.96
3	110	0.82
4	350	24.6
5	1700	23.9
6	2300	13.0

Fig.9 Dimensional configuration of the DCTJ of KLIN cycle.
SLS thrust 37.8 ton, mass 1950 kg.

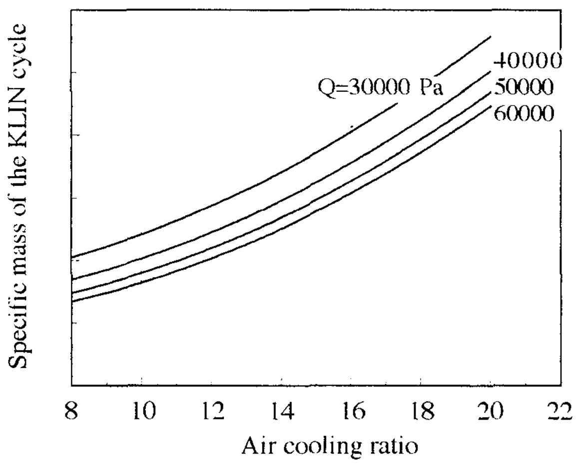


Fig.10 Trend of KLIN cycle mass.