THEORETICAL STUDY OF A NUCLEAR JET ENGINE FOR THE PROPULSION OF AIRPLANES

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Studiul privind utilizare unui reactor nuclear pentru propulsia aeronavelor, poate fi efectuat luand in considerare două soluții posibile: ciclul direct (fluidul de lucru este trecut direct prin reactorul nuclear) şi ciclul indirect (fluidul de lucru este trecut printr-un schimbator de caldură). In această lucrare este prezentat un studiu teoretic complet efectuat asupra soluției ciclului indirect. Atat ciclul termodinamic al motorului turboreactor nuclear cât şi caracteristicile de lucru şi performanțele acestuia au fost calculate. Pentru reactorul nuclear, a fost considerat un model omogen ce foloseşte drept combustibil UO_2, ca moderator BeO, iar barele de control sunt formate din B_4C.

Investigation of the possibility to use a nuclear reactor for the propulsion of airplanes could be performed considering two possible solutions: the direct cycle (the fluid pass through the reactor's core) and the indirect cycle (the fluid pass through a heat exchanger). We report about a complete theoretical study which has been performed for the indirect cycles. The cycles, the characteristics and the performances of nuclear jet engine have been calculated. For the nuclear reactor, a homogenous type using UO_2 as fuel, BeO as neutron moderator and B_4C as the material for the control rods, has been considerate.

Keywords: nuclear reactor, jet engine, propulsion, airplane

1. Introduction

Interest for using nuclear energy for the propulsion of aircrafts appear at the early age of the when the physicists involved in Manhattan project [1]

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(including Enrico Fermi and Richard Feynman) present some possibilities to use the nuclear power in aviation. From all of them, the idea of nuclear propulsion for vehicles on land, sea, and in the air, has been considerate. There were proposals for nuclear ships, nuclear locomotives, nuclear automobiles, and nuclear aircraft. Since the nuclear propulsion for ships concretised in a very short time, it seems that the nuclear propulsion of aircrafts will be soon available.

Starting from 1946, the interest for nuclear airplanes brings to a long-lived project: NEPA (Nuclear Energy for the Propulsion of Aircraft) [2]. The project was oriented towards developing both an atomic- powered long-range strategic bomber and high-performance aircraft. From 1951, the NEPA (renamed ANP – Aircraft Nuclear Propulsion) project have been split on two: one directed by General Electric Co., which plans to develop a direct-cycle turbojet solution, and one developed by Pratt & Whitney Aircraft Division of United Aircraft Corp. was authorized to study the indirect cycle solution. For the direct cycle solution some experiments have been performed, with relatively high success: an engine that uses only nuclear energy was constructed and tested, proving the viability of the solution [3]. The indirect cycle was investigated only at the level of testing different type of materials [4]. The main problems regarding the aircraft nuclear propulsion are the weight of the reactor and of the protection devices. ANP project shows that a nuclear facility of 80 tones could offer sufficient protection and energy for a nuclear jet engine. Both solutions have been abandoned at the beginning of 1960s.

The soviet project Tupolev 119 (Tu-119) also known as Tu-95 LAL – (Flying Nuclear Laboratory) [5], was focused on the investigation of different shielding solutions, but, approximately in the same time with the US projects, it has been also cancelled.

In the present, the idea of nuclear propulsion for airplanes was not completely forgotten [6]. The development of so-called micro nuclear reactors [7] of low weight and high power could bring to a feasible solution which can represents an opportunity for the aviation industry, considering also the continuously increase of the oil's price. Modern simulation techniques [8,9] could bring new solution regarding the heat exchange at very high air's velocity.

2. The thermodynamic cycles of the nuclear jet engine

In the direct-cycle solution, the working fluid (in this case, the air) enters through the compressor stage of the engine and from there is directed through the reactor core where it is acting as coolant for the reactor. In the reactor chamber (which replaces the burning room of a classic turbojet engine), the air is rapidly heated and is directed to the turbine section and from there out through the tailpipe [10]. In the indirect system case, the air does not pass through the reactor's core. After passing through the compressor stage, the air is directed through a heat exchanger, which takes the heat generated by the reactor and transfer it to the air. The working fluid of the heat exchanger, could be a liquid metal, or highly pressurized water or air.

The main difference between the two solutions arises from the fact that in the indirect-cycle case, the nuclear reactor is completely isolated from the environment, so this solution seems to be more feasible than the other one. Based on this fact, in this paper, a complete theoretical study of the indirect-cycle solution was performing.

Considering fact that the working fluid is the air on all the engine's sections (no burned gases are present), some hypothesis should be established in order to continue the study of the thermodynamic cycle of the engine [11]:

1. the evolution of the fluid in the admission and in the evacuation areas are isenthalpic
2. no energy transfers in the admission and in the evacuation areas are present
3. the compression and the extending evolutions are adiabatic and non isentropic
4. the evolution in the heat exchanger area is polytrophic very close to an isobaric one
5. the extending process in the evacuation area is complete
6. the cycle is closing on the atmospheric pressure.

To complete the study, the construction and working parameters of the engine should be defined and selected . For the nuclear jet engine, the parameters are not different from a regular turbojet engine, since the only difference between them is the heat exchanger that replaces the combustion chamber. The selected values of the parameters are [12]:

- $\sigma_{da} = P_1^*/P_H^* = 0.98$ – coefficient of the pressure loss in the admission area, where P_1^* is the pressure at the entrance in to the compressor's section, and P_H^* is the pressure of the atmosphere at H altitude.
- $\sigma_{ca} = P_3^*/P_2^* = 0.97$ – coefficient of the pressure loss in the heat exchanger area, where P_3^* and P_2^* are the pressure values at the exit and at the entrance in to the heat exchanger area.
- $\eta_c = l^*_{cid}/l^*_c = 0.86$ – adiabatic efficiency of the compressor, where l^*_{cid} and l^*_c are the work required by the compressor in the ideal and real case respectively.
- $\eta_m = P_c/P_T = 0.98$ – mechanical efficiency of the turbo-compressor group, where P_c is the power of the compressor and P_T is the power of the turbine.
- $\eta_T = l^*_T/l^*_{Tid} = 0.89$ – adiabatic efficiency of the turbine, where l^*_{Tid} and l^*_T are the turbine work in the ideal and real case respectively.

- $\varphi_{ar} = C_5/C_{5id} = 0.98$ – velocity coefficient of the discharge nozzle, where C_5 and C_{5id} are the velocity of the air in the discharge nozzle in the ideal and real case.

- $\pi_{c0} = P^*_2/P^*_1 = 8$ – pressure ratio of the compressor, where P^*_2 and P^*_1 are the pressures at the exit and at the entrance sections of the compressor.

- k = 1.4 – adiabatic exponent of the working fluid (air).

- R = 0.28716 KJ/KgK – universal gas constant

- c_P = 1.005 KJ/KgK – specific heat at constant pressure.

Using the above parameters the stages of the engine's thermodynamic cycles at ground level and in operation could be determined. For the ground level, **stage 0** (H = 0 m and V = 0 m/s) – standard atmosphere is described by:

$$T_0 = T_0^* = 288.3K,\ P_0 = P_0^* = 1.10337\,bar\ , \tag{1}$$

The enthalpy will be:

$$\begin{aligned} i_0 &= i_0^* = c_p \cdot T_0 = 288.3\ KJ/Kg \\ i_0^* &= i_0 + \tfrac{V^2}{2} \end{aligned}\ , \tag{2}$$

The entropy for all stages could be estimated by [12]:

$$s_0 = s_0^* = s_0^{`} - R \cdot \ln(P^*)\ , \tag{3}$$

where:

$$s_0^{`} = A_0 + A_1 \cdot T_0^* + A_2 \cdot T_0^{*2} + A_3 \cdot T_0^{*3} + A_4 \cdot T_0^{*4}\ , \tag{4}$$

and A_0 = 4.941494 KJ/Kg·K, $A_1 = 9.6401265\cdot10^{-3}$ KJ/Kg·K^2, $A_2 = -1.7785936\cdot10^{-5}$ KJ/Kg·K^3, $A_3 = 2.1013955\cdot10^{-8}$ KJ/Kg·K^4, $A_4 = -1.3263673\cdot10^{-11}$ KJ/Kg·K^5.

The thermodynamic parameters for all cycle's stages (1* - the entrance in to the compressor, 2*id, 2* - the exit from the compressor, 3* - the exit of the heat exchanger, 4id, 4 – the exit of the discharge nozzle, 5id and 5) have been calculated based on the equations (1)-(4).

The estimation of the thermodynamic parameters of the nuclear jet engine in operation (H=10.000 m and V=280m/s) is performed using the same equations as above, with the consideration that the *-parameters are not anymore equal with the normal ones. The value of the specific thrust force, in this case, is 607 m/s.

The thermodynamic parameters of the nuclear jet engine's cycles are illustrated in Fig.1 and are presented in Tab.1 and 2.

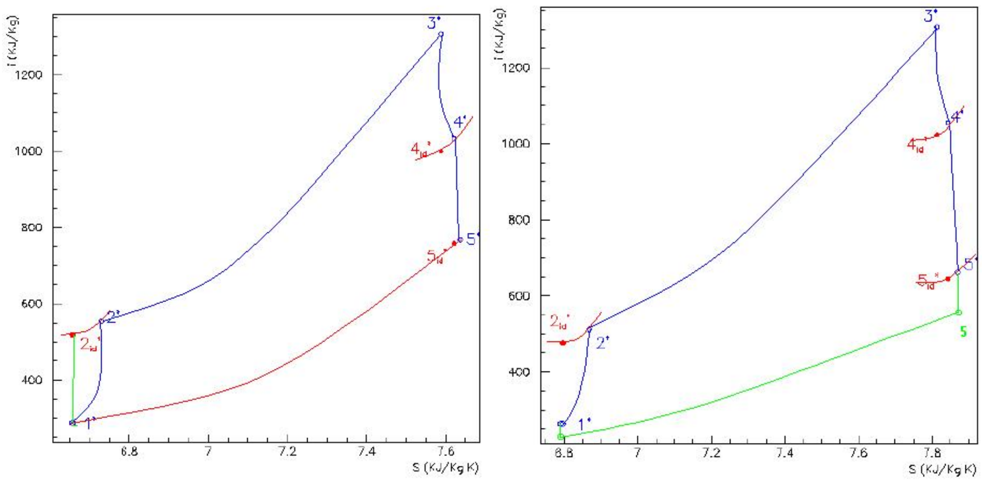

Fig. 1. The thermodynamic cycles of the nuclear jet engine at ground level (left) and in operation H = 10.000 m, V = 280 m/s (right)

Table 1

Parameters of the thermodynamic cycles of the nuclear engine at ground level

Stage	P*[bar]	s*[KJ/KgK]	i*[KJ/Kg]
0	1.013	6.657	288.3
1*	0.993	6.658	288.3
2_{id}*	7.945	6.730	519.2
2*	7.945	6.730	551.0
3*	7.706	7.588	1306.
4_{id}*	3.010	7.588	998.7
4*	3.010	7.621	1033.
5_{id}*	1.013	7.621	756.6
5*	1.013	7.636	767.5

Table 2

Parameters of the thermodynamic cycles of the nuclear engine in operation

Stage	P*[bar]	s*[KJ/KgK]	i*[KJ/Kg]
H	0.458	6.791	263.5
1*	0.448	6.797	263.5
2_{id}*	3.588	6.797	475.8
2*	3.588	6.869	510.4
3*	3.480	7.814	1306.
4_{id}*	1.481	7.814	1023.
4*	1.481	7.844	1055.
5_{id}*	0.265	7.844	645.0
5*	0.265	7.869	661.2

Based on the results we can finally estimate the value of the specific thrust force:

$$F_{sp} = C_5 - V = 728.11\, m/s \tag{5}$$

where:

$$C_5 = C_{5id} \cdot \phi_{ar} = 728\, m/s$$
$$C_{5id} = \sqrt{2 \cdot (i_4^* - i_{5id}^*)} = 743\, m/s \tag{6}$$

3. The operating lines of the nuclear jet engine

The operating lines of an engine are defined as [13] the evolution curves of the engine's performances (in this case the thrust - F) as function of the working parameters (speed - V, altitude - H, rotational speed - n): F $(V)_{n=ct,H=ct}$, F $(H)_{n=ct,V=ct}$ and F $(n)_{H=ct,V=ct}$.

The thrust is defined as:

$$F = \dot{M}_a \cdot F_{sp},\ \ where:$$
$$\dot{M}_a = a \cdot \frac{P^*}{\sqrt{T^*}} \cdot q(\lambda) \cdot A \cdot \sin\alpha \tag{7}$$
$$q(\lambda) = \lambda \cdot \left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \cdot \left(1 - \frac{k-1}{k+1} \cdot \lambda^2\right)^{\frac{1}{k-1}}$$

where: □$_a$ is the air flow rate and q(λ) is the dynamic function of the flow rate [13]. Using the hypothesis that in the narrowest cross-section of the engine (the entrance in the turbine's stator 3'-3') λ_3'=1 (critical regime of the flow rate), for two working condition (at ground and in flight) one obtains:

$$\dot{M}_a \cdot \frac{\sqrt{T_3^*}}{P_3^*} = \dot{M}_{a0} \cdot \frac{\sqrt{T_{30}^*}}{P_{30}^*} \tag{8}$$

Using the conditions:

$$P_3^* = P_H \cdot \pi_d \cdot \sigma_{da}^* \cdot \pi_c^* \cdot \sigma_{ca}^* \ \ and\ \ T_3^* = const. \tag{9}$$

one obtains:

$$\dot{M}_a = \dot{M}_{a0} \cdot \frac{P_H}{P_0} \cdot \left(1 + \frac{V^2}{2 \cdot i_H}\right)^{\frac{k}{k-1}} \cdot \frac{\pi_c^*}{\pi_{c0}^*} \tag{10}$$

Since the work required by the compressor is constant then:

$$\pi_c^* = \left[1 + \frac{i_0 \cdot \left(\pi_{c0}^{*\,\frac{k-1}{k}} - 1 \right)}{i_H + \frac{V^2}{2}} \right]^{\frac{k}{k-1}}$$

$$\dot{M}_a = \dot{M}_{a0} \cdot \frac{P_H}{P_0} \cdot \frac{1}{\pi_{c0}^*} \cdot \left[1 + \frac{V^2}{2 \cdot i_H} + \frac{i_0}{i_H} \cdot \left(\pi_{c0}^{*\,\frac{k-1}{k}} - 1 \right) \right]^{\frac{k}{k-1}} \qquad (11)$$

Finally, the specific thrust is: $F_{sp}=C_5$-V, where:

$$C_5 = \phi_{ar} \cdot \sqrt{2 \cdot \left\{ i_3^* \cdot \left[1 - A^{\frac{1-k}{k}} \right] - \frac{i_0 \cdot \left(\pi_{c0}^{*\,\frac{k-1}{k}} - 1 \right)}{\eta_c^* \cdot \eta_T^* \cdot \eta_m} \right\}}, \ where:$$

$$A = \left[\left(1 + \frac{V^2}{2 \cdot i_H} \right)^{\frac{k}{k-1}} \cdot \sigma_{da}^* \cdot \pi_c^* \cdot \sigma_{ca}^* \right] \qquad (12)$$

Using the same assumptions and supplementary: $l_c^*=ct \cdot n^2$, for the rotational speed operation line, one obtains:

$$C_5 = \phi_{ar} \cdot \sqrt{2 \cdot \left\{ i_3^* \cdot \left[1 - A^{\frac{1-k}{k}} \right] - \frac{i_0 \cdot \left(\pi_{c0}^{*\,\frac{k-1}{k}} - 1 \right)}{\eta_c^* \cdot \eta_T^* \cdot \eta_m} \right\}}, \ where:$$

$$A(n) = \sigma_{da}^* \cdot \left[1 + \bar{n}^2 \cdot \left(\pi_{c0}^{*\,\frac{k-1}{k}} - 1 \right) \right]^{\frac{k}{k-1}} \cdot \sigma_{ca}^*, \ where: \qquad (13)$$

$$\bar{n} = \frac{n}{n_n}, \ where: n_n \ is\ the\ reference\ rotational\ speed$$

The operating lines of the nuclear jet engine ($F(V)_{n=ct,H=ct}$, $F(H)_{n=ct,V=ct}$ and $F(n)_{H=ct,V=ct}$), are represented in Figs.2 and 3.

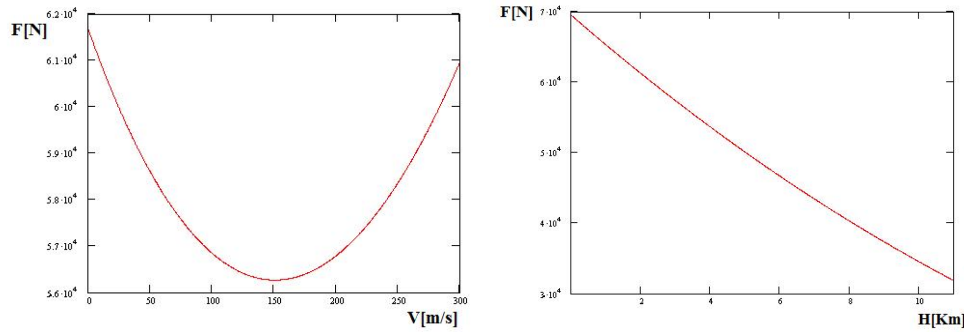

Fig. 2. The operating lines of nuclear jet engine for H,n=ct (left) and V,n=ct (right)

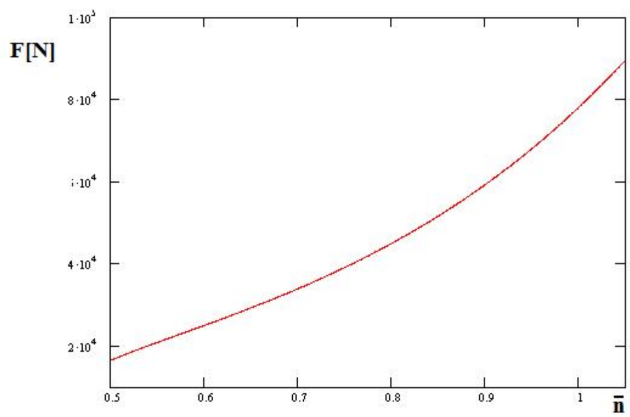

Fig. 3. The operating lines of nuclear jet engine for H,V=ct

4. The heat exchanger

The heat exchanger replaces the combustion chamber on the nuclear jet engine. The main request is to provide the necessary heat to increase the temperature of the air from T_2* (the exit of the compressor) = 554 K up to T_3* (the entrance in the turbine) = 1300 K. Practically, the heat exchanger is a simple pipes system with a diameter of 70 mm (chose due to aerodynamic conditions) each one. Using the data obtained in the previous chapters and some aerodynamic parameters of the air (the coefficient of the heat transfer for air – $\lambda_a = 0.054$ W/m·K; the dynamic viscosity of the air – $\eta_a = 1.165\cdot10^{-4}$ Kg/m·s) the value of the flow rate can be estimated by:

$$\dot{M}_a = \frac{F}{F_{sp}} = 110\ Kg/s \tag{14}$$

The area of the engine in the region of the heat exchanger can be estimate by [12]:

$$A = \dot{M}_a \cdot \frac{\sqrt{T_3^*}}{P_3^* \cdot q(\lambda) \cdot 0.04} = 0.636\, m^2 \tag{15}$$

The velocity of the air and the Reynolds and Nusselt number can be calculated by [14]:

$$w_a = \frac{\dot{M}_a}{A} = 173.02\ m/s$$

$$\mathrm{Re}_a = \frac{\rho_a \cdot w_a \cdot d_e}{\eta_a} = 214600 \tag{16}$$

$$Nu = 1.079 \cdot \mathrm{Re}_a^{0.6} \cdot \mathrm{Pr}_a^{0.33} = 8608$$

Finally, the total heat transfer coefficient and the total surface can be estimated:

$$\alpha_a = Nu \cdot \frac{\lambda_a}{d_e} = 6.641\ KW/m^2 \cdot K$$

$$S = \frac{\dot{M}_a \cdot (i_3^* - {}_2^*)}{\alpha_a \cdot (T_P - T_a)} = 3.1\ m^2 \tag{17}$$

Using an acceptable length of 1.3 m for each pipe, the surface of each pipe can be calculated at: S_{el} = 0.286 m^2, and then the total number of pipes is: N = S/S_{el} = 10. The heat exchanger will be a 10 pipes system of 0.07 m^2 surface and 1.3 m length each (see Fig. 4). The heat transferred from the exchanger to the working fluid is 53.32 MW.

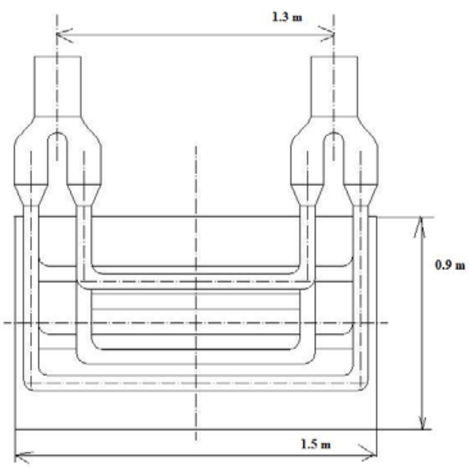

Fig. 4. The heat exchanger

5. The nuclear reactor

For this study, a homogeneous, air cooled, nuclear reactor using UO_2 (5 %) as fuel and BeO (95%) as neutron moderator is considerate [15,16]. The reactor is a cylinder with 1 m radius and 2 m height with a central channel of 10 cm diameter used for the coolant air circulation. The control rods consist of 12 B_4C pieces. The main goal of the reactor is to heat the air from $t_i = 1100^oC$ to $t_z = 1500^oC$. Assuming a constant air flow rate of G = 3 Kg/s, we can estimate the maximum temperature of the reactor core [17]:

$$V = \frac{G}{\rho \cdot A} = 2\ m/s,\ where$$
$$A = 0.729\, m^2\ \textit{is the total cooling surface of the reactor}$$
$$\mathrm{Re} = \frac{V \cdot \sqrt{\frac{4 \cdot A}{\pi}}}{\nu} = 8.303 \cdot 10^4 \tag{18}$$
$$\alpha = Nu \cdot \frac{\lambda_c}{d_{ech}} = 0.018 \cdot ctg\left(\mathrm{Re}^{0.8}\right) = 305.9\ W/m^2 \cdot K$$

Finally, the maximum temperature of the reactor's external wall is calculated as:

$$t_{p\max} = t_z + \frac{S_t}{G \cdot c_p} \cdot \frac{2 \cdot L \cdot q_{v0}}{\pi} \cdot \left[\sin\left(\frac{\pi \cdot z}{2L}\right)\right] + \frac{S_t}{\alpha \cdot 2\pi \cdot R} \cdot q_{v0} \cdot \frac{\pi \cdot z}{2L}$$
$$where:$$
$$z = \frac{2L}{\pi} \cdot arctg\left(\frac{4L \cdot \alpha \cdot R}{G \cdot c_p}\right) = 0.211 \tag{19}$$
$$q_{v0} = \frac{(t_z - t_i) \cdot G \cdot c_p \cdot \pi \cdot 1.6 \cdot 10^{-2}}{S_t \cdot 2L \cdot \left[\sin\left(\frac{\pi \cdot z}{2L}\right) + 1\right]},\ \textit{the heat flow rate}$$
$$S_t = \textit{the frontal area of the reactor}$$

The maximum temperature of the reactor's core will be:

$$t_{\max} = t_{p\max} + \frac{q_{v0}}{2 \cdot \lambda_c} \cdot \frac{R^2}{2} = 2653^o C \tag{20}$$

Since the highest temperature from the reactor's core is smallest then the melting point of UO_2, one can say that this type of nuclear reactor could be used, with success, as energy source for a turbojet engine. The power of the reactor is estimated at aprox. 240 MW.

6. The thermal efficiency of the nuclear jet engine

The thermal efficiency of the nuclear jet engine is defined as the ratio between the total work of the engine and the heat transferred from the heat exchanger:

$$\eta = \frac{L}{Q_p} = \frac{L_t - L_c}{Q_p} \tag{21}$$

where: L_t is the turbine work and L_c is the work required by the compressor. The turbine work could be calculated by:

$$\begin{aligned} &L_t = \dot{M}_a \cdot (i_3^* - i_4^*) + \dot{M}_a \cdot (i_4^* - i_5), \ \ where \\ &i_4^* = i_5^* = i_5 + \frac{C_5^2}{2} \Rightarrow \\ &L_t = \dot{M}_a \cdot (i_3^* - i_4^*) + \dot{M}_a \cdot \frac{C_5^2}{2} = P_T + \dot{M}_a \cdot \frac{C_5^2}{2} \end{aligned} \tag{22}$$

The work required by the compressor can be similarly estimated by:

$$\begin{aligned} &L_c = \dot{M}_a \cdot (i_2^* - i_H) = \dot{M}_a \cdot (i_2^* - i_1^*) + \dot{M}_a \cdot (i_1^* - i_H) \Rightarrow \\ &L_c = \dot{M}_a \cdot (i_2^* - i_2^*) + \dot{M}_a \cdot \frac{V^2}{2} = P_C + \dot{M}_a \cdot \frac{V^2}{2} \end{aligned} \tag{23}$$

Finally, the engine's work and the thermal efficiency will become:

$$\begin{aligned} &L_c = \dot{M}_a \cdot \frac{C_5^2}{2} - \dot{M}_a \cdot \frac{V^2}{2} = 22.68 \ \ MW \\ &\eta = \frac{L}{Q_P} = 42.5\% \end{aligned} \tag{24}$$

The global efficiency of the nuclear jet engine is defined as the ratio between the engine's work and the total power of the reactor:

$$\eta = \frac{L}{P_{reactor}} = 9.5\% \tag{25}$$

7. Conclusions

This study demonstrates that the nuclear propulsion of aircraft is a realistic and feasible solution, especially for the airplanes that are designated to long distance flight, based on the fact that fuel consumption is principally 0. A possible layout of the nuclear jet engine is illustrated in Fig.5.

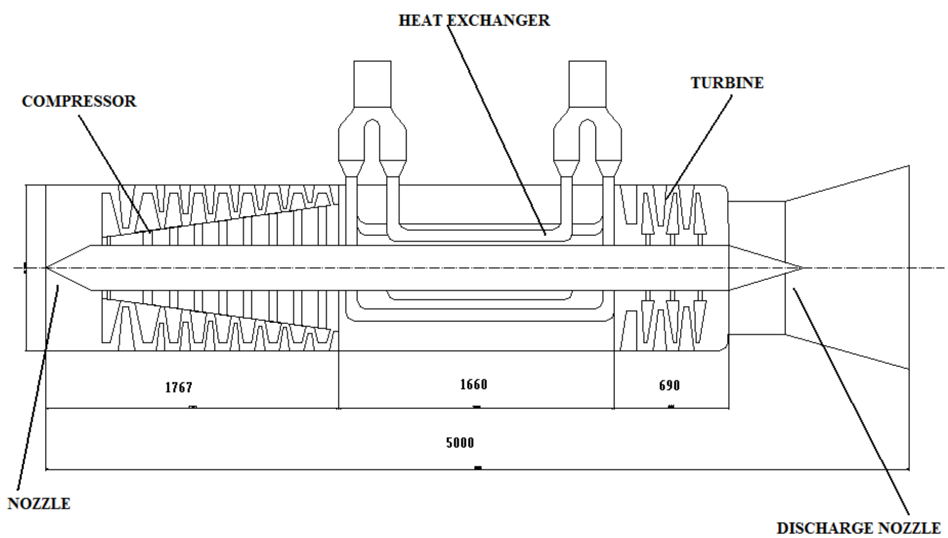

Fig. 5. A sketch of the nuclear jet engine

Preliminary gas-dynamic study of the real cycle of the nuclear jet engine what considerate realistic conditions of this type of engine has been performed. Theoretical study of the heat transfer in correlation with the realistic conditions of the project's tasks has been also performed. The thermal properties of the engine's heat exchanger material (Cr-Ni alloy) have been considerate for this study. Simulations regarding the high fluid's speed heat transfer by using computer programs available on the market (ex: FLUENT [8]) are in progress in order to have a more realistic view of the nuclear jet engine's working conditions (the air flow's parameters in the heat exchanger area).

A very important aspect for the nuclear jet engine is the radioprotection problem. Solutions using multiple protection layers, in order to reduce the total weight of the nuclear reactor, was investigated in the past [18] and the result shows that a total mass (reactor + shielding) of 100-200 tones could be achieved. This represents a reasonable weight taking in to account that for large airplanes (ex.: Boeing 747) only the fuel tank has a capacity of 200 tones. Monte-Carlo simulation using GEANT [19] and FLUKA [20] codes are in progress to study some possible shielding solution.

A very important problem, which is presently in study, is the possibility to release radioactive materials in to the atmosphere, in the case of a possible accident.

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