R-Jet Engineering

TURBOGEN CHP

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Small Recuperated Turbo-Fan Engines

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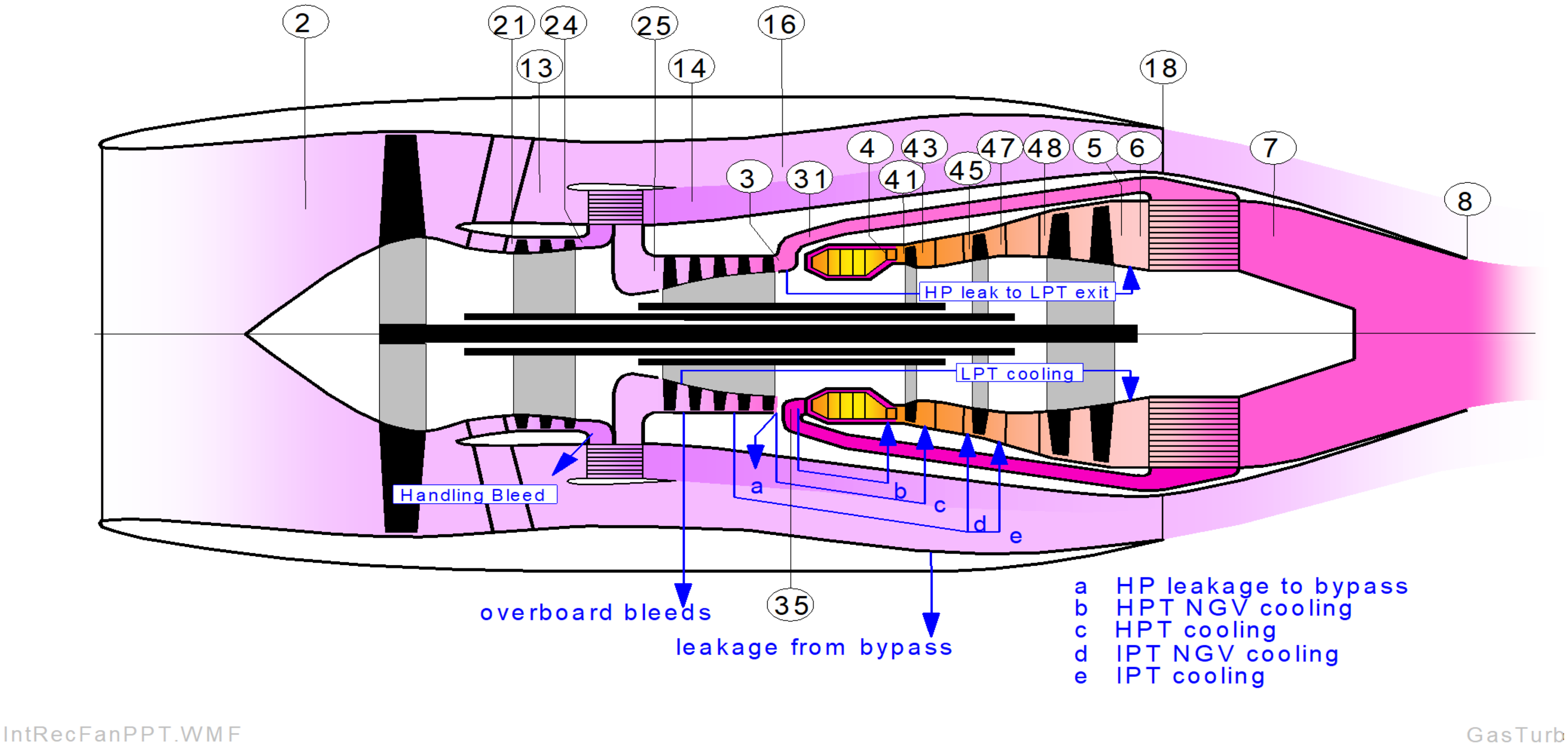


Stations of Recuperated Turbo-Fan

In recent aero-engine core concept development, heat exchangers have been seriously considered as a key technology for higher energy efficiency, particularly in the form of intercooler and recuperator components.
Low overall pressure ratio (OPR) turbofans can benefit from the use of recuperators, by recovering waste heat from the exhaust gas, while intercoolers provide a way to increase thrust at high OPRs.

Furthermore, the studies of the combination of both techniques have showed persistent advantages on thermal efficiency for a wide OPR range .(See Figs 1,2).

Turbofan recuperated aero engines design has been evaluated by IRA European program (See references last slide) in 2005-2016 .Several recuperator designs have been presented in which the recuperator is placed in the engine exhaust flow heating the compressor exit air flow thus reducing fuel consumption. Further investigation of the recuperated fan engine cycle reveals that the overall engine pressure ratio (currently between **30-45** in modern engines) may be reduced to lower values (between 6-15) when installing the recuperator, while keeping the same fuel consumption .

The low Overall core Pressure Ratio(OPR) reduces the engine weight and cost. These low OPR recuperated engines have thus a potential to improve aircraft performance and cost.

Recuperator is justified if the **reduced fuel weight is higher than its added weight**.

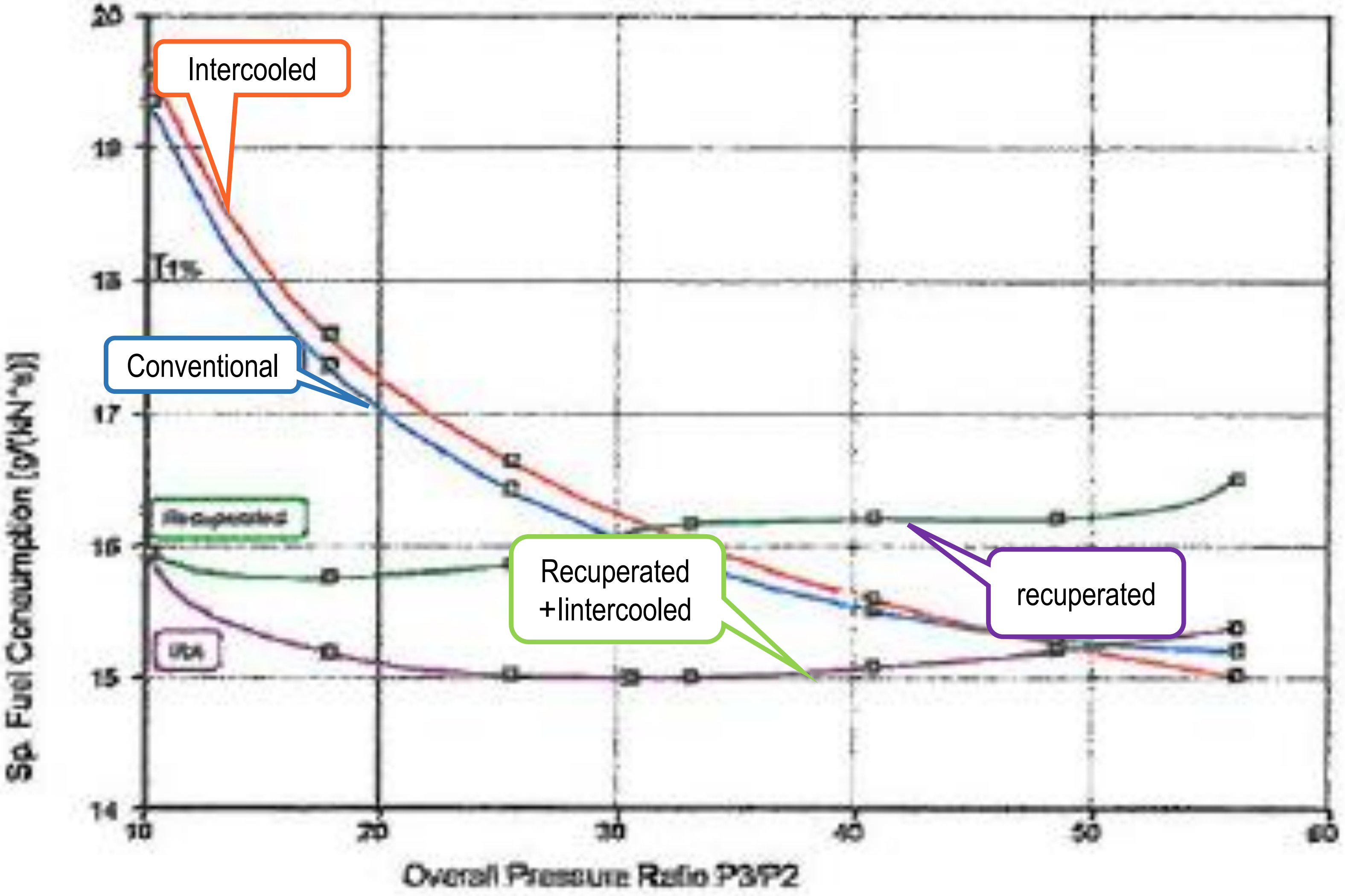


Fig 1: T.S.F.C As function of O.P.R
Alt- 12000m Mach-0.8   Turb inlet temp-1600k

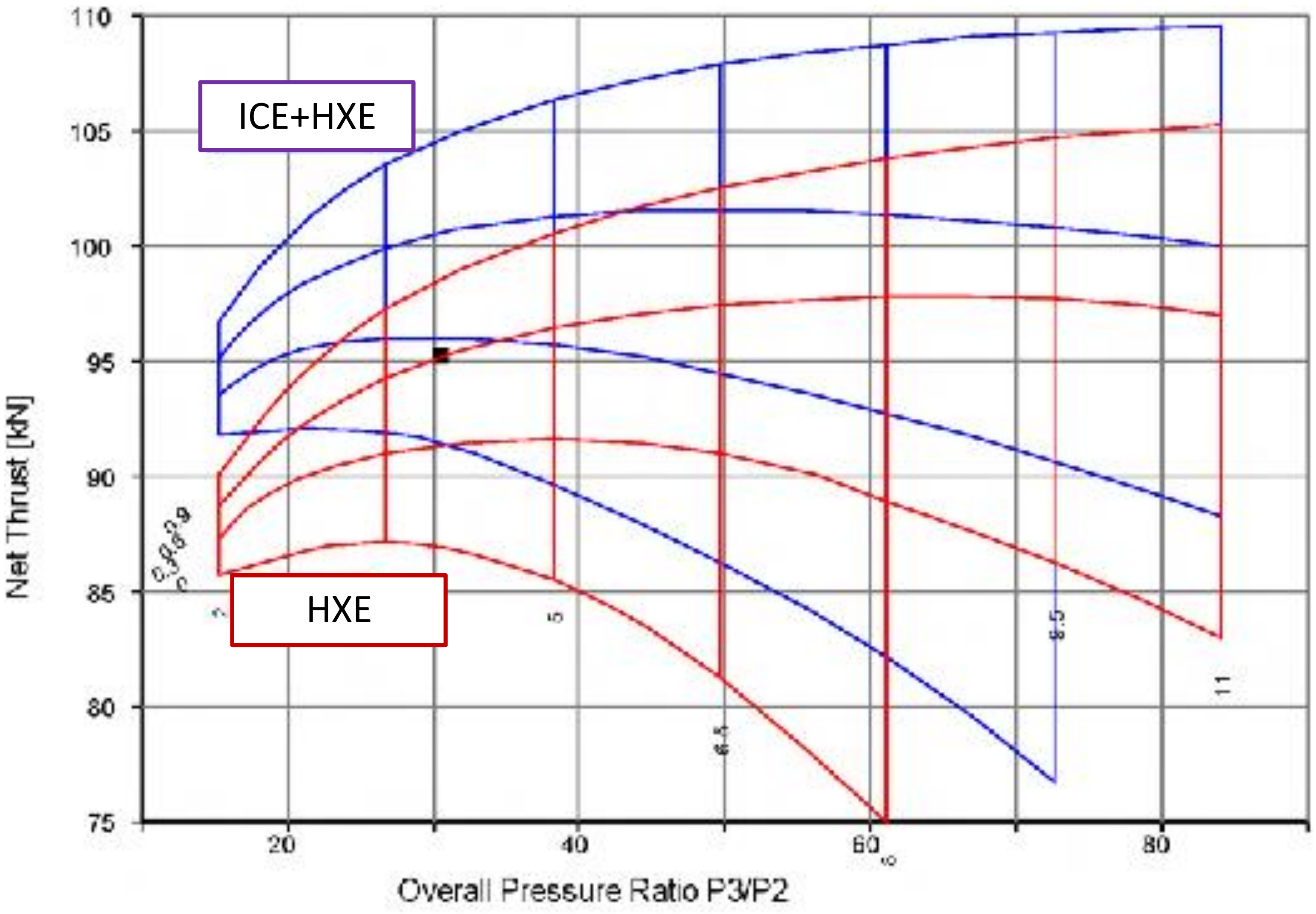


Fig 2: Effect of ICE and HXE on net Thrust

HXE- Heat Exchanger; ICE – Inter Cooler

4
31

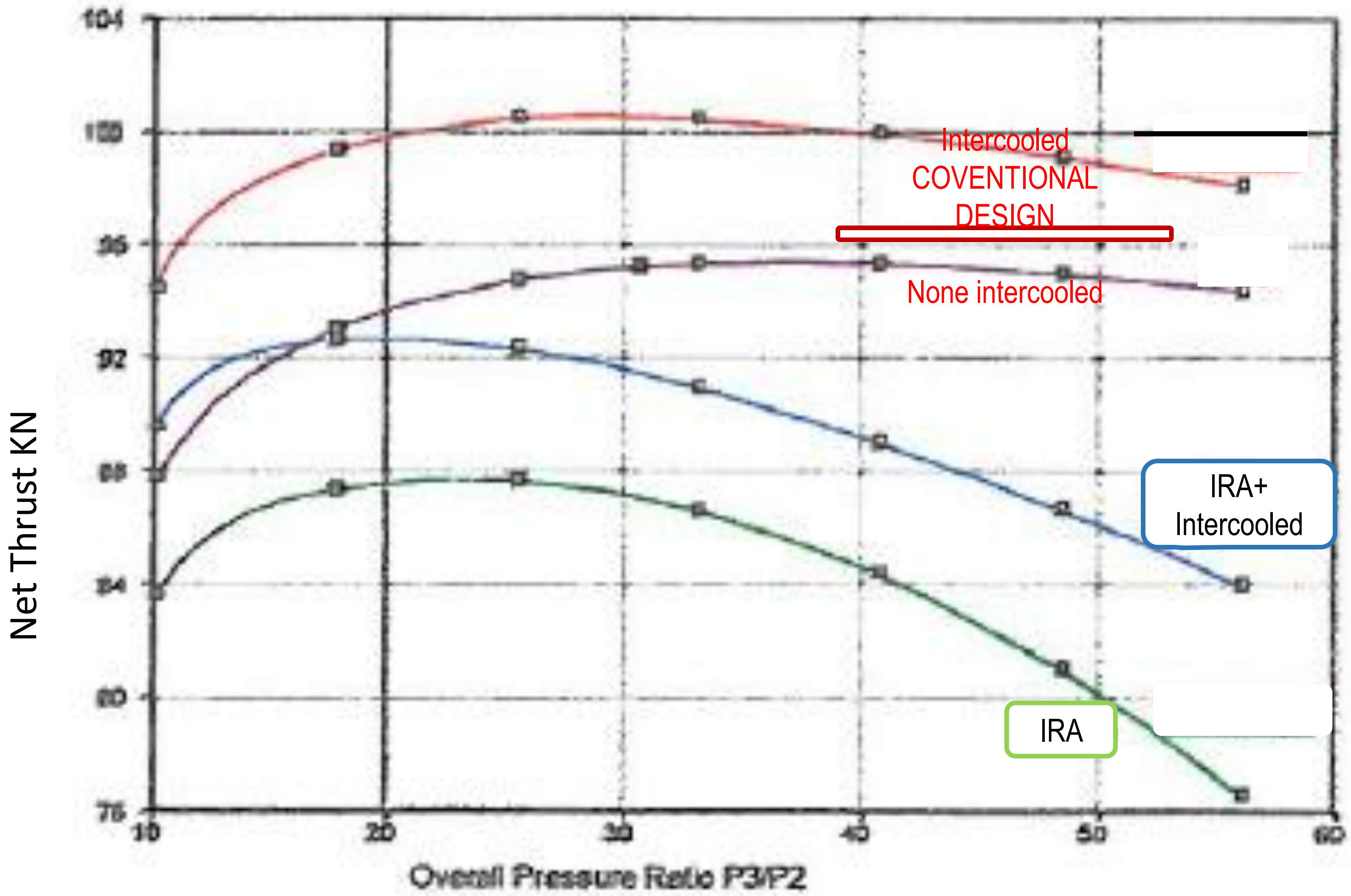


Fig 3- Net Thrust As function of O.P.R
Alt.12000m Mach-0.8. Turb. Inlet temp.-1600k

In the past aero-engine heat exchanger research, porous media CFD has been applied frequently in the early stage of the development as a relatively convenient and inexpensive approach. Later, a conical shell and tube recuperator has been designed.

The optimization efforts resulted in two completely new innovative heat exchanger concepts, named as CORN -Conical Recuperative Nozzle and STARTREC -Straight Annular Thermal 9). (see fig.4)

The two new concepts provided significant benefits in terms of fuel consumption, pollutants emission and weight in relation to more conventional heat exchanger designs proving that further optimization potential for this technology exists.

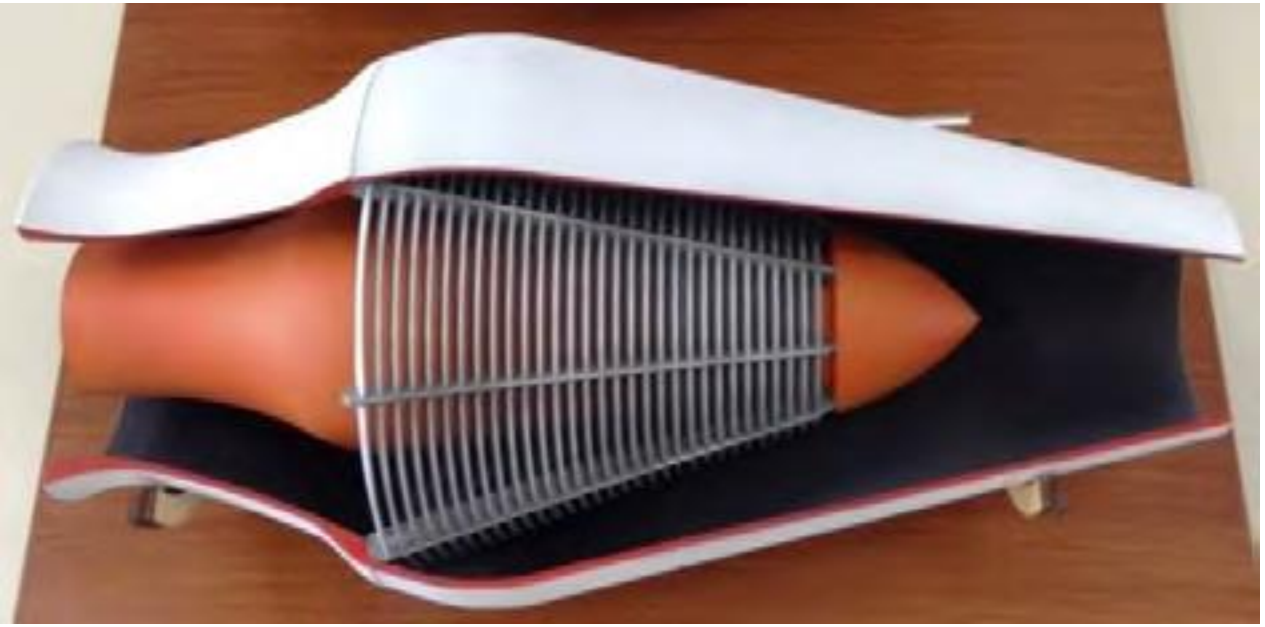
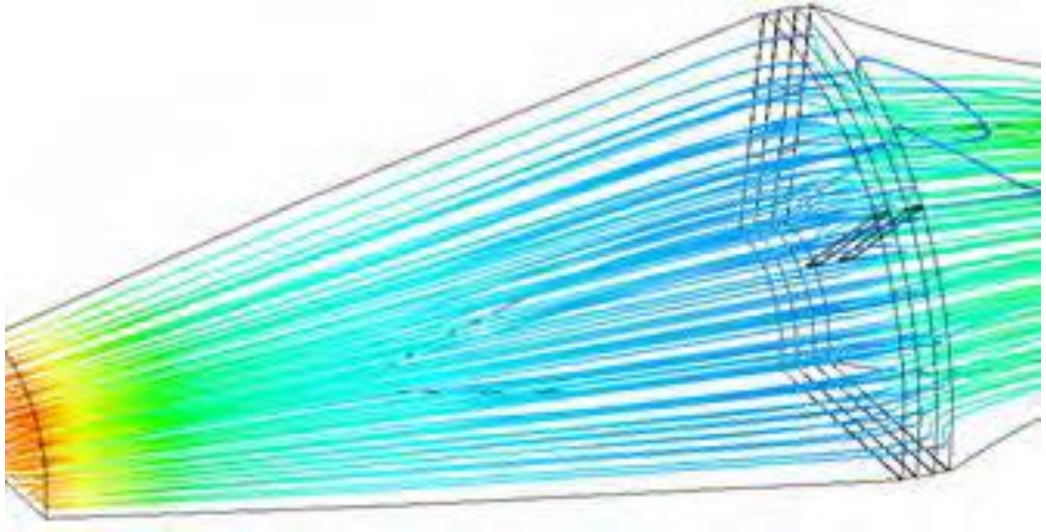


Fig 4a: CORN (COnical Recuperative Nozzle)

Fig 4b:-STARTREC design



Considering the high investments to modify current high O.P.R gas turbines:

1. Adding a recuperator to existing low O.P.R engine and also adding 2 major ducts to convey the cold and hot flow of the recuperator.
2. Modify the combustor to accept the hotter air inlet flow.
3. Modify exhaust system
4. Modify fan system

Manufacturers will not adapt such recuperator design.

It is suggested that this technology will be adapted to future small turbofans for long flight hours, commercial or military applications.

Small turbofans low O.P.R recuperated /intercooled design specifications

Small turbofans are specified here as follows-

S.L at 0 speed core air flow - 1.5 kg/sec.

Uncooled turbine .

O.P.R<10.

Design point-12000 meter Mach NO.-0.8

By-passed recuperator.(max take-off thrust)

Dry weight-less than 100 kg.

S.L. take-off thrust >2.50 KN

2 shaft design.

			Altitude - Meters		
			12000	12000	12000
O.P.R			**33.2**	**13.9**	**7.64**
W	Kg/Sec	Total	15	15	15
		Core	0.59	0.586	0.59
Thrust	KN		0.85	0.79	0.72
WF	Gr/Sec		12.7	11.5	10.8
Tsfc	Gr/KN		14.85	14.65	15.07
Core Eff.	%		69	71.6	69
Propulsion Eff.	%		72	74	75.7
T	k		1606	1606	1600
B.P.R			7.0	7.0	7.0
Recuperator Eff.	%		80	80	80

			Altitude - Meters		
			S.L	S.L	S.L
O.P.R			**23.24**	**8.83**	**5.25**
W	Kg/Sec	Total	12.2	14.18	11
		Core	1.445	1.372	1.437
Thrust	KN		3.54	2.85	2.72
WF	Gr/Sec		32.4	26	29.4
Tsfc	Gr/KN		9.0	9.14	10.79
Core Eff.	%		52.3	47	41.2
Propulsion Eff.	%		0	0	0
T	k		1536	1438	1543
B.P.R			7.35	7.07	6.6
Recuperator Eff.	%		50	53.2	51

Table 1:
small turbofan
Low O.P.R.
performance

M=0.8;   12,000 M
BPR = 7.0
Recuperator efficiency 80%

M=0   at   S.L
BPR = 7.0
Recuperator efficiency 51%-53% 52%

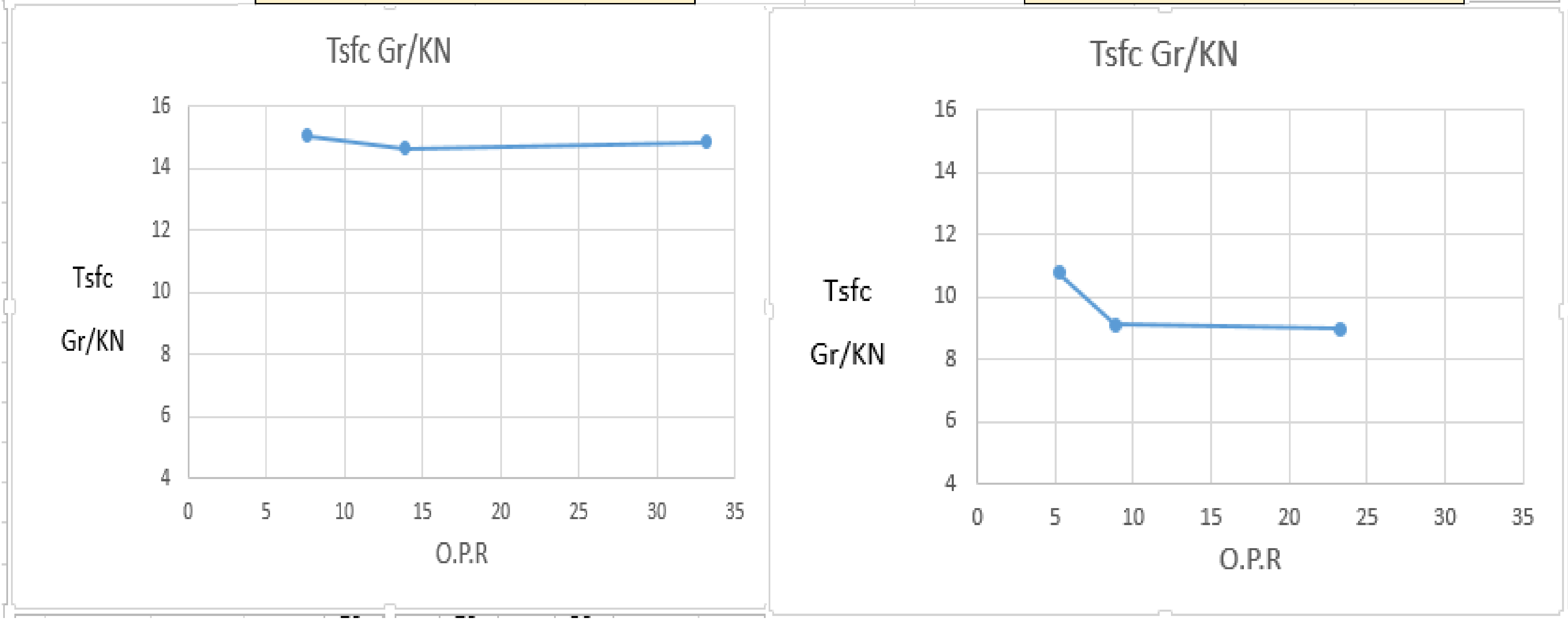


Fig 5: TSFC as function of O.P.R

Small recuperated turbofan design

Input design conditions

1. Turbine inlet temperature-1340k[none cooled]
2.Design point-altitude=12000m . Mach number=0.8
3. Thrust at design point>0.6 KN4
4. T.S.F.C<16 gr/sec.KN
5.Total engine weight=75kg.
6. 2 shaft design.
7. Compressor axial radial design.
8. By pass split design recuperators.

Design point results at 12000 m, M=0.8.

Thrust -0.66KN

Fuel flow-10.1 gr/sec{**without recuperator 16.6 gr/sec**]

Fuel weight gain per hour=	19.8 kg/hr
T.S.F.C-	15.3gr/KN*s
Spool speed-	69000 rpm
Fan spool speed-	23000 rpm
B.P.R-	6
O.P.R-	7.5
TURBINE INLET temp-	1334k
Recuperator weight-steel-	40kg
Engine weight-	35kg
Total weight-	75 kg

Conclusion:

Recuperator is beneficial after 2 hours of flight.

It will save 200kg of fuel after 12 hours of flight.

Off design results at S.L

THRUST-	2.5KN
T.S.F.C-	10.4gr/KN*s
O.P.R-	5.0
B.P.R-	6
RECUPERATOR EFF.-	54%

This low efficiency is due to the increased density and velocity Of cold flow at sea level condition.

LPC Design

Input:

LPC Tip Speed	m/s	310.00000
LPC Inlet Radius Ratio		0.35000
LPC Inlet Mach Number		0.58000
Engine Inl/Fan Tip Diam Ratio		1.00000
min LPC Inlet Hub Diameter	m	0.00000

Output:

LPC Tip circumf. Mach No		1.02155
LPC Tip relative Mach No		1.17472
Design LP Spool Speed	[RPM]	**17899.1**2
LPC Inlet Tip Diameter	**m**	**0.33077**
LPC Inlet Hub Diameter	m	0.11577
Calculated LPC Radius Ratio		0.35000
Aerodynamic Interface Plane	m^2	0.08593
Corr.Flow/Area LPC	kg/(s*m^2)	198.92585

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Efficiencies:          isentr  polytr    RNI      P/P
  Outer LPC           0.8700  0.8798  0.350    1.750
  Inner LPC           0.8600  0.8701  0.350    1.700
  IP Compressor       0.8400  0.8526  0.484    1.800
  Intercooler         0.8000           0.9800
  HP Compressor       0.8500  0.8678   0.806    2.500
  Burner              0.9995           0.9215
  HP Turbine          0.8800  0.8755   0.331   1.416
  IP Turbine          0.8700  0.8672   0.254   1.234
  LP Turbine          0.8800  0.8613   0.216    3.746
  Heat Exchang        0.8000                    0.9800
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Small turbofan Engine—SPLIT 2 HEAT EXCHANGERS DESIGN

A preliminary recuperated small turbofan design is presented in which the recuperator design is split into 2 heat exchangers one at the exhaust and the second at combustor inlet, both connected by a fluid flow transferring heat energy. [Reference 1]

This design results in low gas turbine weight and TSFC for all recuperated gas turbine cycles.

Split recuperator system description. Fig.10

A recuperated turbofan design is presented in which the recuperator is split into 2 heat exchangers one at the exhaust and the second at combustor inlet or last stage compressor outlet. The 2 heat exchangers are connected by a fluid system which does not completely evaporate at turbine outlet temperature.

The high density of the fluid compared to gas fluid results in a compact mechanical design replacing state of art air to gas recuperators which need large ducts to convey the gas and air from the recuperator to the combustor and from the compressor outlet to the recuperator with low pressure losses.

One suitable solution is to use a CO_2 fluid at a super critical condition pressure of 50- 600 bars. At this pressures the CO_2 is beyond its critical point and behaves like a dense fluid even at high temperature (fig.10).

At the recuperator in the exhaust side the CO_2 fluid acts as a cooler [absorbing heat from the turbine exhaust gas]. The recuperator cold efficiency increases if the G*Cp value of the fluid decreases. ,

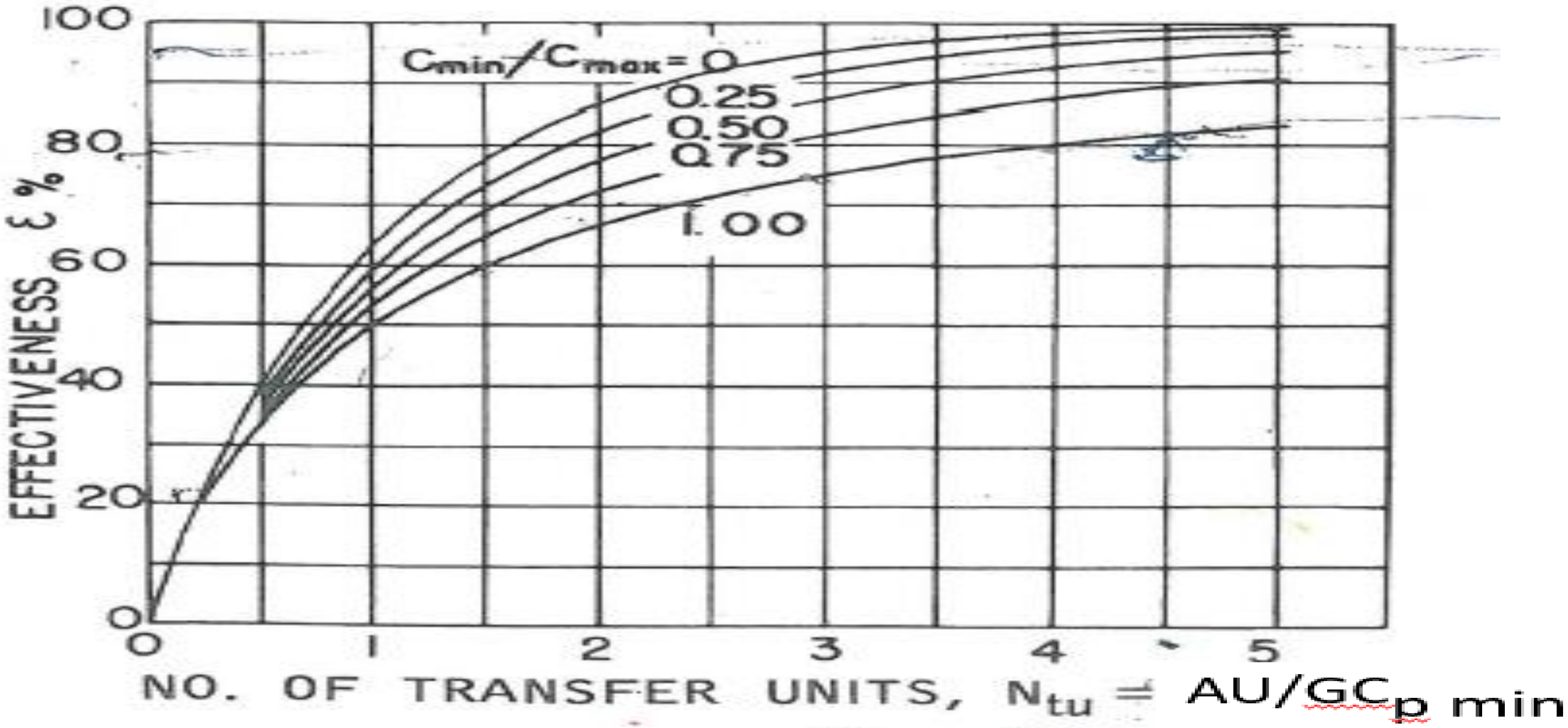
Where-

G=fluid mass flow

Cp=pressure constant kj/kg.c

At the recuperator in the compressor outlet side the CO2 acts as a heater, so for achieving best recuperator efficiency the GCp value must be increased. It is suggested that the best way is to keep the fluid mass constant and to change the Cp value by controlling its pressure.

Fig 6 Heat transfer effectiveness as a function of number of transfer units and capacity rate ratio; counterflow exchanger.



$C=G*C_p$

Control system

Fig.7 describes the CO_2 fluid system which includes a closed pressurized tubular system in which the pressure is regulated by electric driven pump. The pump speed and pressure is controlled by the max. inlet temperature. For each temperature the optimum GCp value is achieved by changing the pressure value.

By controlling the CO_2 pressure we are able to optimize the GC.p to have an optimum value for each operating condition [altitude ,speed] resulting in a compact system having an optimum heat exchanger efficiency for each condition ,thus reducing fuel flow.

If $C_L > C_c > C_h$
In Which C=G*Cp

Then
$\varepsilon_{total} = (Tc_2 - Tc_1)/(Th_1 - Tc_1)$

Th_1 – Fixed by turbine outlet temperature
Tc_1 – Fixed compressor outlet temperature

Therefore only Tc_2 may increase ε_{total} Value

This may be done by Increasing GxCp of CO_2 Flow b
control of circulating pressure value.

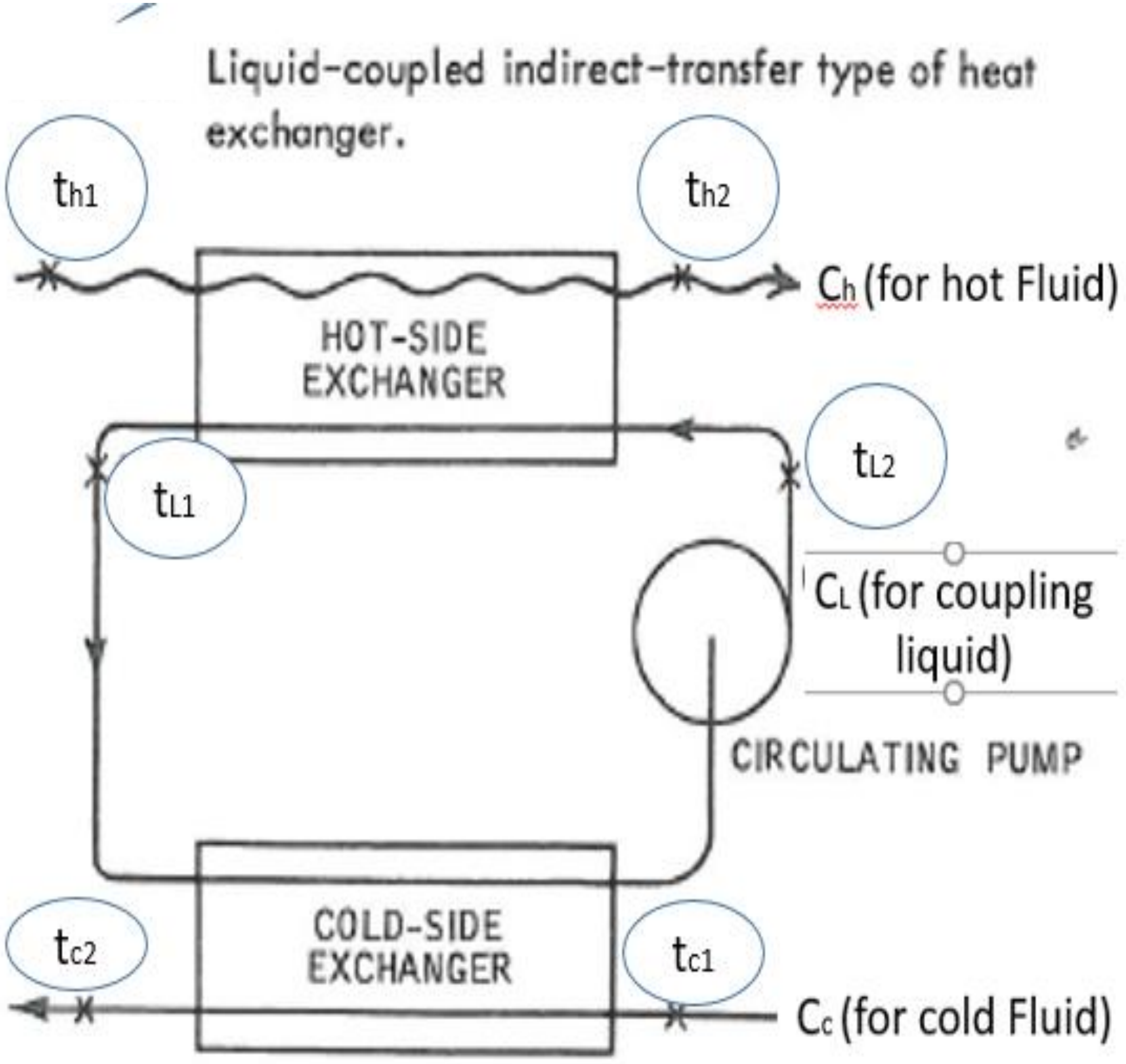


Fig 7: Split recuperator Flow System diagram

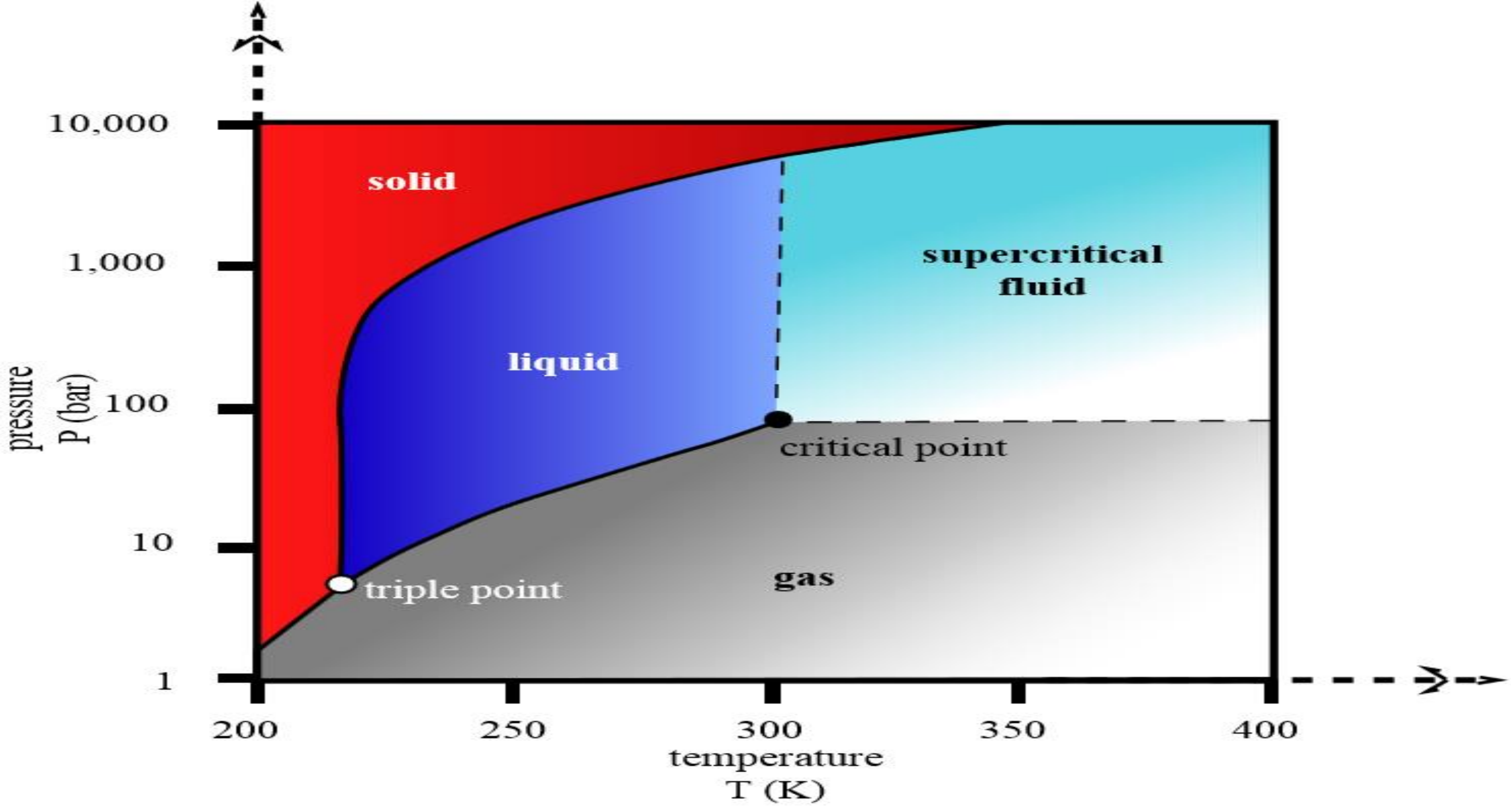


Fig 8- CO_2 Fluid characteristics

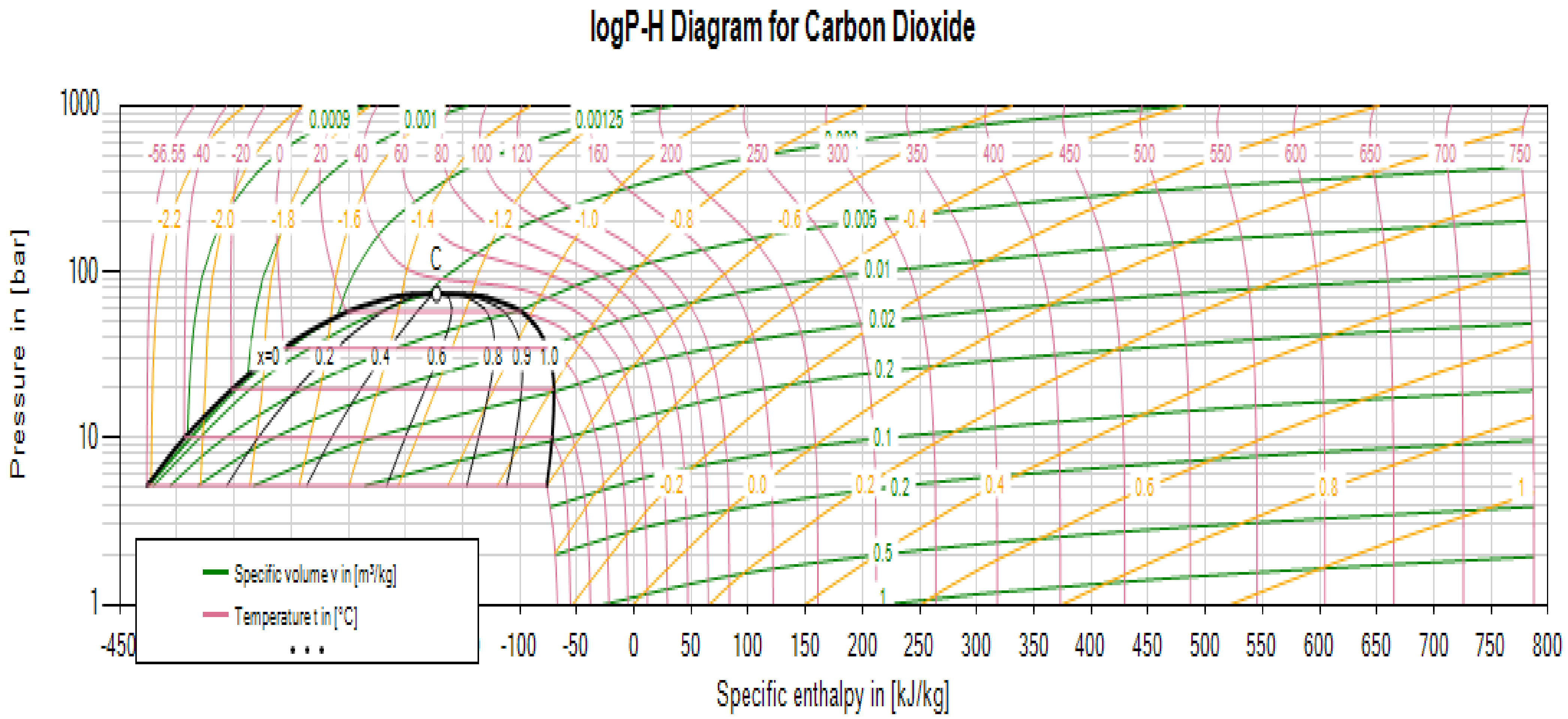


Fig.9- SCO$_2$ P-H diagram. Example- in a temperature of 500 C when pressure is decreased from 150 to 50 bars The Cp value is reduced from 1.23 to 1.08 kj/kg*C-this 15% improvement improves the heating effectiveness of the cold heat exchanger by 6%. The green lines above show the specific volume which is also controlled by the pressure.

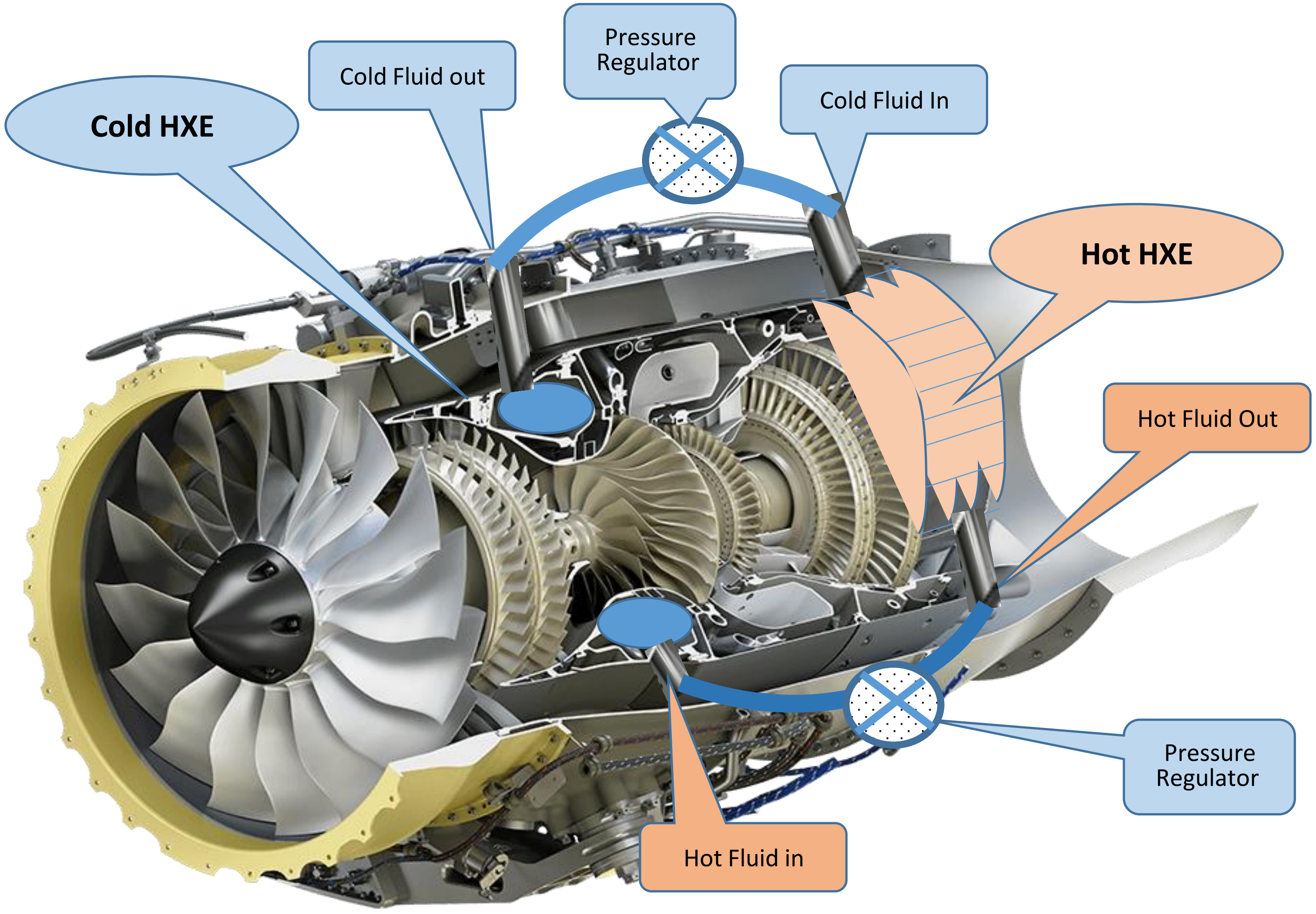
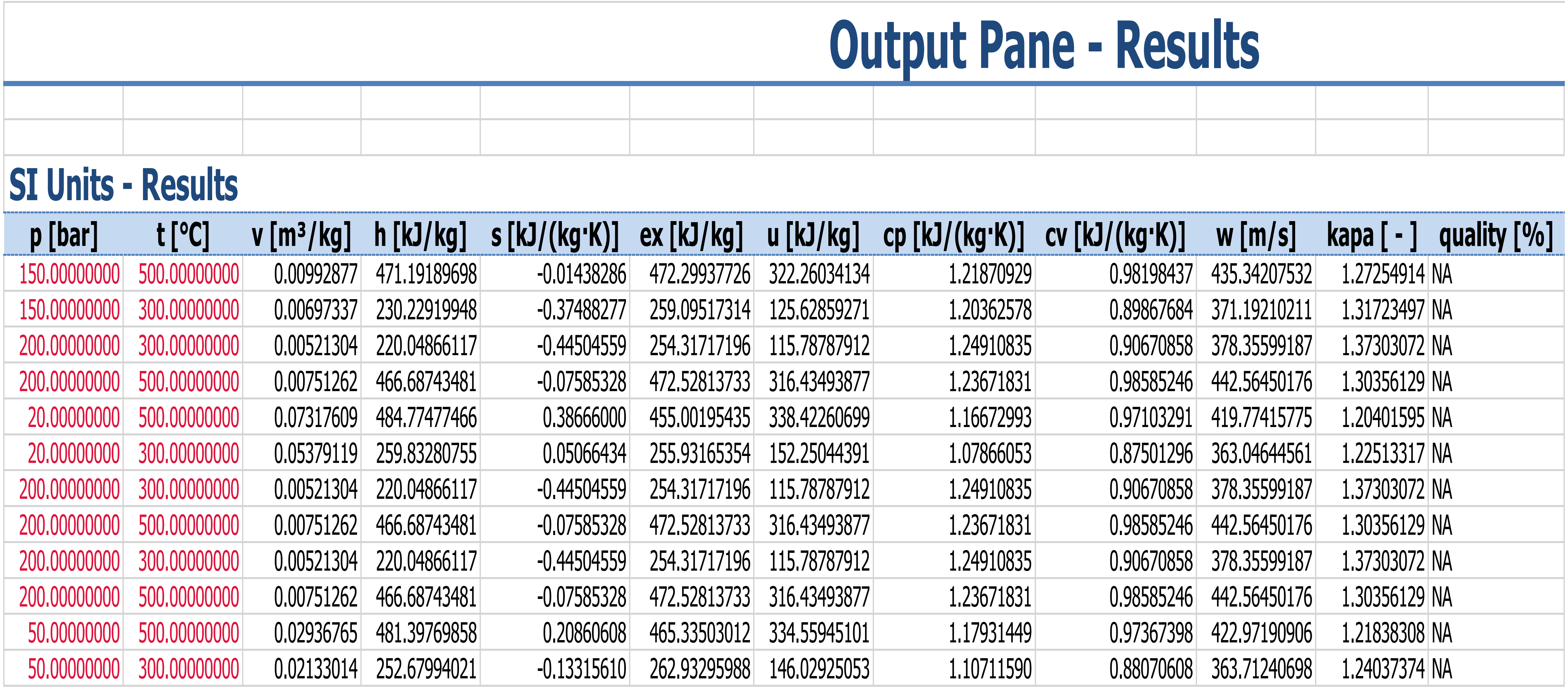


Fig.10—split heat exchanger turbofan system

Table 3-CO_2 Cp as function of pressure &temperature



Output Pane - Results

SI Units - Results

p [bar]	t [°C]	v [m³/kg]	h [kJ/kg]	s [kJ/(kg·K)]	ex [kJ/kg]	u [kJ/kg]	cp [kJ/(kg·K)]	cv [kJ/(kg·K)]	w [m/s]	kapa [-]	quality [%]
150.00000000	500.00000000	0.00992877	471.19189698	-0.01438286	472.29937726	322.26034134	1.21870929	0.98198437	435.34207532	1.27254914	NA
150.00000000	300.00000000	0.00697337	230.22919948	-0.37488277	259.09517314	125.62859271	1.20362578	0.89867684	371.19210211	1.31723497	NA
200.00000000	300.00000000	0.00521304	220.04866117	-0.44504559	254.31717196	115.78787912	1.24910835	0.90670858	378.35599187	1.37303072	NA
200.00000000	500.00000000	0.00751262	466.68743481	-0.07585328	472.52813733	316.43493877	1.23671831	0.98585246	442.56450176	1.30356129	NA
20.00000000	500.00000000	0.07317609	484.77477466	0.38666000	455.00195435	338.42260699	1.16672993	0.97103291	419.77415775	1.20401595	NA
20.00000000	300.00000000	0.05379119	259.83280755	0.05066434	255.93165354	152.25044391	1.07866053	0.87501296	363.04644561	1.22513317	NA
200.00000000	300.00000000	0.00521304	220.04866117	-0.44504559	254.31717196	115.78787912	1.24910835	0.90670858	378.35599187	1.37303072	NA
200.00000000	500.00000000	0.00751262	466.68743481	-0.07585328	472.52813733	316.43493877	1.23671831	0.98585246	442.56450176	1.30356129	NA
200.00000000	300.00000000	0.00521304	220.04866117	-0.44504559	254.31717196	115.78787912	1.24910835	0.90670858	378.35599187	1.37303072	NA
200.00000000	500.00000000	0.00751262	466.68743481	-0.07585328	472.52813733	316.43493877	1.23671831	0.98585246	442.56450176	1.30356129	NA
50.00000000	500.00000000	0.02936765	481.39769858	0.20860608	465.33503012	334.55945101	1.17931449	0.97367398	422.97190906	1.21838308	NA
50.00000000	300.00000000	0.02133014	252.67994021	-0.13315610	262.93295988	146.02925053	1.10711590	0.88070608	363.71240698	1.24037374	NA

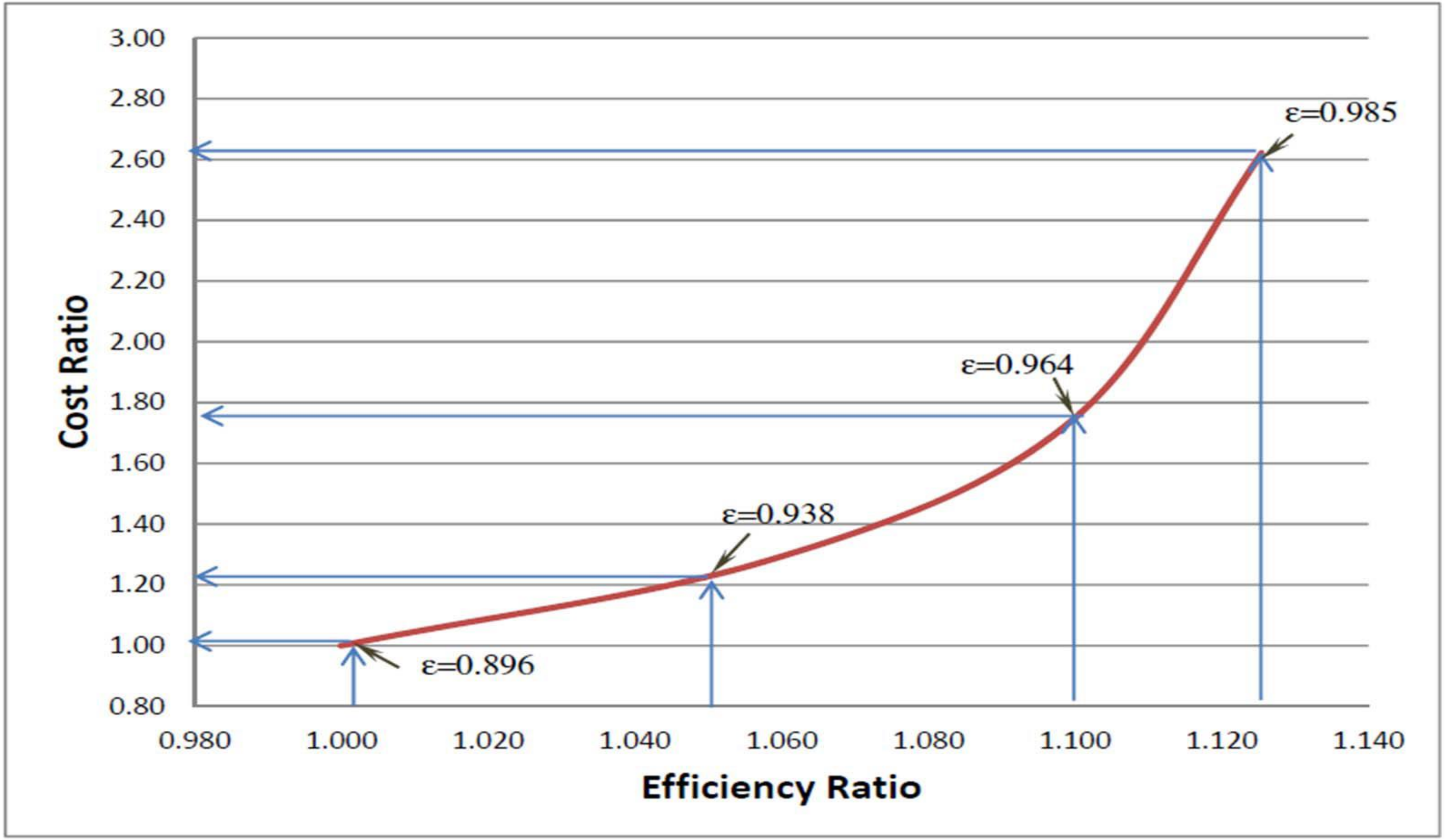


Fig 11- PCHE recuperator efficiency

summary

- A split heat exchanger system (minimum 2 heat exchangers connected by a fluid system) in which one is attached to the compressor outlet and transmitting its heated fluid flow into the combustor and a second attached to turbine exhaust outlet and transmitting its heated fluid flow into the first heat exchanger.
- A CO_2 fluid closed system transmitting heat energy between above heat exchangers.
- A controllable CO_2 fluid operating pressure which optimizes both recuperators heat transfer performance, thus reducing its fuel consumption.
- A compact split heat exchanger design adaptable to other gas turbines like turbo shaft and turbo propeller engines.

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