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A GAS TURBINE PROPULSION PLANT WITH THE CAPABILITY TO PROVIDE STEAM FOR BOTH INJECTION AND AIRCRAFT CATAPULTS

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ABSTRACT

Proposed in this paper is a novel propulsion system. On the basis of a gas turbine Brayton cycle a Rankine regenerative cycle was set up in parallel, which by utilizing the waste heat of the gas turbine exhaust gas is able to flexibly supply steam for gas turbine steam injection and for aircraft catapults. Thus brought forth is a gas turbine propulsion plant with a dual-purpose steam supply, which can well be suited for use on board an aircraft carrier. The propulsion plant under discussion has the inherent merits of a steam injected gas turbine cycle, but the additional new feature of steam supply for aircraft catapults significantly enhances the advantages of the propulsion plant as a whole. With a medium-sized aircraft carrier being selected as an example a comprehensive comparison has been conducted of four types of propulsion power plants, including a gas turbine propulsion plant with the capability to supply steam for both gas turbine steam injection and aircraft catapults.

INTRODUCTION

It is well known that gas turbines have a multitude of merits, such as a low engine specific weight, quick start-up, compactness, system simplicity, ease of maintenance and a high thermal efficiency, etc. Because of the above, they are very popular among naval and marine engineering circles. Approximately forty countries have employed gas turbines to serve as naval or merchant marine propulsion plants for a total of roughly 3000 naval vessels and ships with 3000 gas turbines engines being installed worldwide and the total installed capacity amounting to nearly 49, 000, 000 hp. However, conventional steam power plants and nuclear propulsion ones still dominate the realm of large-sized aircraft carriers either now in active service or under construction and the use of gas turbines has been confined to relatively light aircraft carriers of helicopters and vertical take-off and landing aircraft. This is caused in part by the fact that gas turbines can only provide naval vessel main propulsion power and, in contrast to nuclear and steam power plants, are incapable of supplying steam of required parameters in a convenient and timely manner for use in a steam-driven catapult for the catapult launching of carrier-borne aircraft.

In addition, the relatively large air consumption of gas turbines also gives rise to some inconveniences in engine and deck space layout. On the other hand, since the official commercial operation of the first in the world steam injected gas turbine (STIG) in early 1985, the ensuing few years have seen dramatic advances in the development of such STIG plants, which are mainly employed for power generation or the simultaneous production of electrical energy and process heat.

The Harbin Marine Boiler & Turbine Research Institute has long been engaged in the research of the STIG technology. After undergoing a period of experimental study three sets of PG5361 STIG cogeneration plants were put into commercial operation in 1992 at Shenzhen City in China. Meanwhile, there appeared in recent years a full spectrum of papers devoted to the discussion of the STIG concept being applied to naval vessel propulsion. [1][2][3] and [4]

It is against the foregoing background that the authors have come up with a novel concept which consists of the following. On the basis of a gas turbine Brayton cycle a Rankine regeneraive cycle was set up in parallel, which by utilizing the waste heat of the gas turbine exhaust gas is able to flexibly supply steam for gas turbine steam injection and also for aircraft catapults. Thus brought forth is a gas turbine propulsion plant with a dual-purpose steam supply, suitable for use on board an aircraft carrier.

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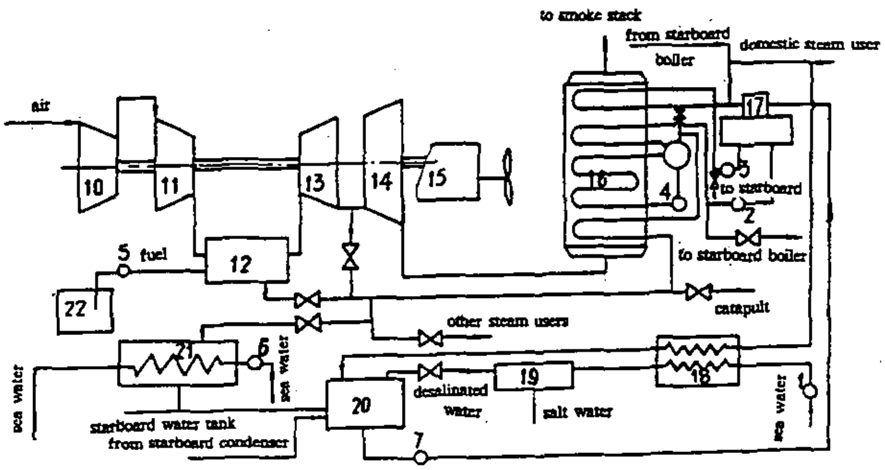

Fig. 1 Schematic Diagram of a Main Propulsion Plant (Version 1)

1	high-pressure sea water pump	2	high-pressure feedwater pump
3	low-pressure feedwater pump	4	boiler circulating pump
5	fuel oil pump	6	sea water circulating pump
7	desalinated water pump	10	low pressure compressor
11	high pressure compressor	12	combustor
13	high pressure turbine	14	power turbine
15	reduction gear	16	heat recovery boiler
17	deaerator	18	sea water heater
19	sea water desalination plant	20	day water tank
21	by-pass steam condenser	22	day oil tank

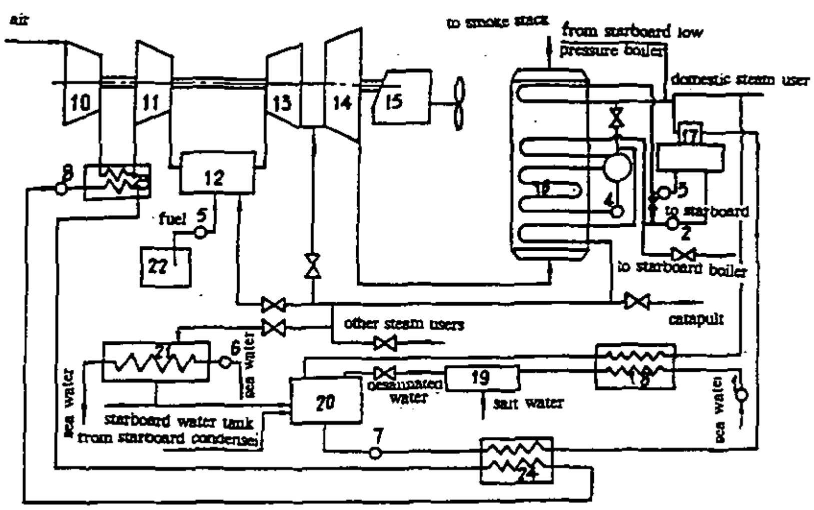

Fig. 2 Schematic Diagram of a Main Propulsion Plant (version 2)

1	high-pressure sea water pump	2	high-pressure feedwater pump
3	low-pressure feedwater pump	4	boiler circulating pump
5	fuel oil pump	6	sea water circulating pump
7	desalinated water pump	8	intercooling circulating pump
10	low pressure compressor	11	high pressure compressor
12	combustor	13	high pressure turbine
14	power turbine	15	reduction gear
16	heat recovery boiler	17	deaerator
		18	sea water heater
19	sea water desalination plant	20	day water tank
21	by-pass steam condenser	22	day oil tank
23	intercooler	24	feedwater heater

A GAS TURBINE PROPULSION PLANT WITH THE CAPABILITY TO PROVIDE STEAM FOR BOTH INJECTION AND AIRCRAFT CATAPULTS

Fig. 1 shows a schematic drawing of the main propulsion system proposed in the present paper. As mentioned above, the system has the outstanding feature of the setting up on the basis of a Brayton cycle of a parallel Rankine regenerative cycle which is capable of supplying steam for both gas turbine steam injection and aircraft catapults.

Air as a working medium after being compressed in compressor 10, 11 enters combustor 12. Sea water is pumped into sea water heater 18 through a high-pressure sea water pump 1 and after being heated enters sea water desalination plant 19. Properly desalinated water is stored in water tank 20 to serve as a second working medium, which after going through feedwater pump 7 and deaerator 17 flows into heat recovery boiler 16. In the heat recovery boiler the water absorbs waste heat from turbine exhaust gases and is transformed into superheated steam and then injected into combustor 12. In turbine 13, 14 a mixed working medium composed of two working mediums (gas, steam) does expansion work, and finally exhausts to the atmosphere through heat recovery boiler 16. When the aircraft catapults need to be put into operation, one may decrease gas turbine steam injection rate and the gas turbine begins to work under a partial steam injection mode, thus making it possible to supply enough steam into the aircraft catapults. If the gas turbine does not need any steam injection and the aircraft catapults are not required to operate, the steam produced by the heat recovery boiler 16 can be led into steam condenser 21 through a multi-stage pressure and temperature reduction device. With the condensate being recovered and stored in water tank 20 a closed cycle is formed. The low pressure steam is mainly employed for deaeration heating in deaerator 17 and for desalination heating of seawater in seawater heater 18. The remaining steam can be supplied through a low-pressure steam main to a naval vessel domestic steam system. It is not difficult to perceive that in the case of steam injection and aircraft catapult operation the working steam shall be eventually exhausted to the atmosphere (some can be recovered in a condensing unit). As a result, there arises the need for a rather large seawater desalination plant to replenish desalinated water.

The diagram in Fig. 2 is in principle identical with that shown in Fig. 1 except that in Fig. 2 in addition to the adoption of steam injection, an intercooler 23 has been installed between low-pressure compressor 10 and high-pressure compressor 11, resulting in a decrease in the wasted work of the high-pressure compressor. In this regard, what really counts is the fact that with the outlet air temperature of the high-pressure compressor being lower than that which exists in the case of a corresponding simple cycle coupled, in addition, with a relatively high heat-carrying capacity of steam, it is possible under the condition of steam-gas mixture being used as a blade cooling medium to raise the gas turbine inlet temperature while keeping the blade metal temperature at the original level. As a result, such a ISTIG plant shall has a higher efficiency and a greater specific power. This is demonstrated in Table 1, where the performance data of LM5000 single cycle, LM5000 STIG 120 cycle and LM5000 ISTIG cycle are compared.

DESCRIPTION OF MAIN EQUIPMENT ITEMS AND SYSTEMS

Steam Injected Gas Turbine

There exist in a steam injected gas turbine cycle 4 independent variables: gas turbine inlet temperature, compressor pressure ratio, heat input rate and steam/air ratio. Fig. 3 depicts at a given turbine inlet temperature the general relationship existing among steam injected gas turbine cycle efficiency, specific power, steam/air ratio and pressure ratio.

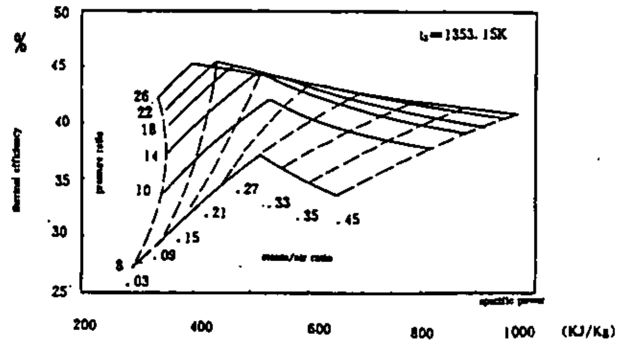

Fig. 3 General Relationship among STIG Cycle Efficiency, Specific Power, Steam/Air Ratio and Pressure Ratio

The key issue of a steam injected gas turbine cycle consists in the selection of proper cycle parameters or a rational matching between various components to attain a high efficiency or high specific power. Taking into account the compactness of a heat recovery boiler in respect of size and power plant economics, it is appropriate for an aircraft carrier to have the steam/gas ratio of the design point selected in the neighborhood of a maximum efficiency point. On the basis of overall structural considerations and the requirements of performance matching and coordination, steam may be injected into any one or several of the following locations: combustor fuel nozzles, combustion liner mixing-dilution holes, compressor outlet diffusing section and power turbine inlet, etc. The steam injection will result in an increase in compressor pressure ratio and a decrease in surge margin. The attainment of a new throughput capacity necessitates a proper adjustment of the turbine flow path, i.e. a corresponding change in the gas turbine structural design and the addition of a corresponding steam injection system.

Heat Recovery Boiler

By absorbing gas turbine exhaust gas heat the heat recovery boiler produces steam. When a gas turbine is operating under a non-steam injection mode, the "exhaust gases" are in the form of gas, but in the case of operation under a steam injection mode, the "exhaust gases" assume the form of gas plus steam.

Since the dimensions, volume and weight of a heat recovery boiler account for a relatively large proportion of the power plant as a whole, the heat recovery boiler of an aircraft carrier should be as compact in size as possible. Moreover, due attention has to be paid to the achievement of a good maneuverability. Consequently, here the design philosophy shall focus not on a high steam output through the maximum use of exhaust gas waste heat but on the attainment of a compromise solution by properly weighing such conflicting factors as steam output, heat recovery boiler dimensions and weight. For a naval vessel the selection of a forced circulation heat recovery boiler is to be highly recommended. The initial steam parameters shall simultaneously meet the requirements of aircraft catapulting and steam injection. In view of this, the steam pressure should be determined on the basis of catapulting requirements and once determined shall remain unchanged. This runs counter to the case of a combined gas and steam turbine cycle, where under a sliding pressure operating mode the steam pressure varies, depending on the gas turbine loads. To ensure the temperature requirements of catapulting operations and steam injection, the superheater heating surfaces are calculated with a proper reserve margin and a steam regulating device is provided on pipe lines.

When a heat recovery boiler is designed as a dual-pressure one, the high-pressure steam will be intended for steam injection and the catapults, while the low-pressure steam is used for deaeration heating and sea water desalination heating as well as for naval vessel domestic steam supply system.

The heat recovery boiler should be designed to permit "dry firing". When certain components of a heat recovery boiler suffer from malfunctions or are required to operate under abnormal conditions, the heat recovery boiler can engage in a dry mode operation. In the meanwhile, the basic gas turbine shall be able to continue providing power for a naval vessel or craft.

Steam By-pass System

The installation of a steam by-pass system has the following aims: to exhaust steam during engine start-up and shut-down as well as in case of engine emergency shut-down, to discharge excess steam during steam injection or catapulting operations, to maintain a steam-feedwater thermal system cycle in cases when a gas turbine is operating but the steam injection and the catapulting system have not been put into operation, and to avoid triggering in ordinary conditions the opening of heat recovery boiler safety valves. At this juncture a "ready for action" condition prevails when steam supply is available at any time for conducting steam injection or initiating a catapulting operation.

The steam by-pass system mainly comprises: a pressure reduction by-pass valve, a multi-stage pressure and temperature reduction device and a steam condenser, etc. The pressure reduction by-pass valve features a fast response control function so that under all loads during the cessation of steam supply for steam injection or catapulting the said valve can open quickly to avoid the popping of safety valves caused by an excessively high steam pressure at the heat recovery boiler outlet. The steam condenser fulfills the function of condensing the steam it has received into water. To prevent an excessively large temperature difference in the steam condenser, the steam prior to entering the steam condenser flows through a multi-stage pressure and temperature reduction device, in which boiler feedwater is used as desuperheating water. The condenser cooling surface area shall be designed on the basis of the heat recovery boiler maximum output. However, a proper subcooling level should be maintained through proper control in order to avoid an excessively high oxygen content in the water. The condenser uses sea water to serve as a cooling medium.

Sea Water Desalination System

When steam is used for gas turbine steam injection or for aircraft catapulting, its consumption can be rather high, making it necessary to replenish an enormous amount of high-quality desalinated water. In addition to other quality indexes, the injected steam should be such that its sodium plus potassium content is equal to or less than 15 microgram/kg. In terms of quantity, for example, a propulsion plant of 200,000 hp operating for 24 hours needs a daily replenishment of above-cited water amounting to 3,000 cubic meters, thus necessitating the installation of a huge-size sea water desalination plant. In reality, the full-speed or nearly full-speed navigation time of large-sized surface craft only accounts for a very small percentage of their total navigation time. Statistics data show that the number of hours spent by an aircraft carrier navigating at a speed of 28 knots is only about

3% of its total navigation time, while at the speed of below 20 knots the figure is 80%. However, the following two factors should be taken into account when making a compromise in deciding on the actually needed capacity of a desalination plant: 1. a naval vessel has been provided with a desalination water storage tank of a given capacity; 2. during its cruising at low speed a naval vessel has the possibility of conducting a continuous process of sea water desalination and the resulting uninterrupted accumulation of desalinated water.

At any rate, the realization of sea water desalination of a given capacity at a moderate penalty of weight, volume and energy consumption is of great importance to a naval vessel. The main types of sea water desalination plants include multiple-stage flash-separation, multiple-effect evaporation and reverse osmosis.

THE PERFORMANCE OF A PROPULSION SYSTEM WITH THE CAPABILITY TO PROVIDE STEAM FOR BOTH INJECTION AND AIRCRAFT CATAPULTS

To make a concrete evaluation of the performance of the said system, the authors have selected a medium-sized aircraft carrier (Kiev class) to serve as a specific object of study. The chief requirements stipulated for the main propulsion plant include the following:

The 4-shaft propulsion plant has a total propulsion power of no less than 170,000 hp, a maximum speed of no less than 30 knots and a cruising speed of 18 knots, at which its corresponding shaft power is about 32,000 hp and its endurance not lower than 8,000 nautical miles. The aircraft catapult speed is about 27 knots. The aircraft carrier has two steam-powered catapults with a maximum steam consumption rate of 2 × 36 t/hr. The steam is provided by the main propulsion plant. The performance of the whole propulsion plant has been evaluated with respect to the system shown in Fig. 1 and on the basis of the following conditions: ambient temperature 27 ℃, atmospheric pressure 1. 013 bar, sea water temperature 25 ℃.

Steam Injected Gas Turbine

The performance of the basic gas turbine selected and that of the steam injected gas turbine following a STIG-oriented modification are given in Table 2, in which the said performance has been obtained based on the following conditions: ambient temperature 27 ℃, inlet air total pressure loss 2 kpa, exhaust gas pressure loss respectively 3 kpa and 7. 75 kpa, fuel oil low calorific value 42700 kj/kg.

The variation of specific fuel consumption of the steam-injected gas turbine with its output power is shown in Fig. 4.

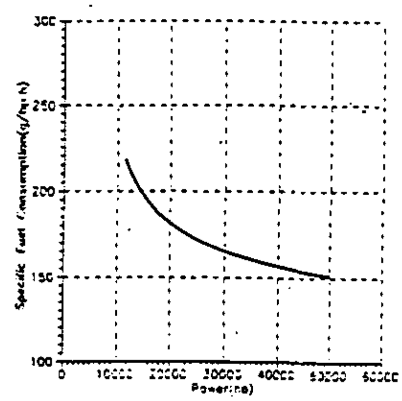

Fig. 4 Variation of Specific Fuel Consumption with Output Power

Heat Recovery Boiler

The heat recovery boiler is of a dual-pressure and forced circulation type. The high-pressure steam is used for steam injection and aircraft catapulting. The intended applications of the low-pressure saturated steam include water deaeration heating and sea water desalination heating with the remaining steam (if available) for meeting partially the naval vessel domestic steam consumption needs. The heat recovery boiler with a vertical smoke uptake is located at the upper portion of the gas turbine exhaust exit. Table 3 lists the performance data of the heat recovery boiler.

There is in the present propulsion system also a 50 t/h oil-fired boiler with the same steam parameters (temperature and pressure) as those of the heat recovery boiler to provide a backup steam source for the steam-powered catapults.

Sea Water Desalination Plant

The desalinated water storage tank of the aircraft carrier is assumed to have a capacity of 124 t. This is equivalent to a water quantity sufficient to sustain a full speed navigation of the carrier for one hour. The capacity of the sea water desalination plant (without counting the whole ship requirement) is taken to be 1610 cubic meters per day, a sufficient quantity to enable the propulsion system operating at a relatively low steam injection rate to undertake a sustained navigation at a speed of 27 knots. So long as the naval vessel speed is lower than 27 knots, the sea water desalination plant will have excess water continuously deposited in the storage tank. At a cruising speed of 18 knots the time for accumulating a water quantity sufficient to meet the needs of one-hour full speed navigation shall be 3. 5 hours.

The sea water desalination plant selected pertains to a reverse osmosis type whose characteristics are given in Table 4.

Steam By-pass Condenser

The heat load of a shell-tube type condenser made of titanium alloy tubes is calculated by proceeding from the assumption that the steam of two heat recovery boilers after flowing through respectively a multi-stage pressure and temperature reduction device exhausts to a single condenser. For the main characteristics of the condenser, please refer to Table 5.

Propulsion Plant Layout

Arranged in pairs and located respectively in the two front and rear machinery compartments, the four steam injected gas turbines are connected to adjustable pitch propeller shafts through their respective reduction gears. (See Fig. 5.)

The two units of gas turbines in each main machinery compartment constitute an independent entity. The two heat recovery boilers in the same compartment with a main line-based feedwater system share a single deaerator. The steam injection system and steam bypass system of each gas turbine are respectively independent, but the by-pass system of the two gas turbines shares one condenser. Fig. 6 illustrates a transverse section of the turbine engine layout in the rear machinery compartment.

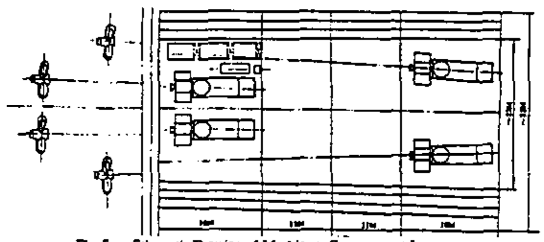

Fig. 5 Schematic Drawing of Machinery Compartment Layout

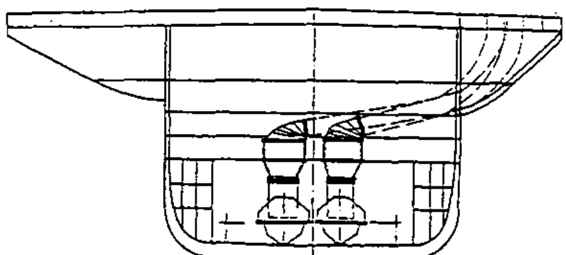

Fig. 6 Transverse Section of Turbine Layout in the Rear Machinery Compartment

Operating Mode

With the four steam injected gas turbines operating at full load the total shaft power at the reduction gear output flange end shall be 193,400 hp, and can ensure a top speed in excess of 31 knots. When cruising at 18 knots, the turbines need a propulsion power of about 32,000 hp with the main power plant being able to operate under a variety of power combination modes.

During a catapulting operation, a special mode of operation, it is necessary to have a navigation speed higher than 27 knots. However, in this case the majority of the steam is spent on two catapults (about 2 × 36 t/hr) with only a small part of the steam being used for injection (steam/gas ratio around 4%), but the total shaft power should attain 130,000 hp in order to ensure the necessary speed for catapult launching. Consequently, the four main engines shall operate under a condition featuring a relatively high turbine inlet temperature (higher by 90 ℃ as compared with the turbine inlet temperature during a corresponding power output specific to a normal steam injection operation) and a relatively low efficiency (its fuel consumption higher by 13 g/hp. hr as compared with that during a corresponding power output specific to a normal steam injection operation). Of course, the total time that the engines work under such operating conditions is of short duration. Upon completion of all catapult operations or in the event of using only one catapult all will be normal.

Speed-up Characteristics

A steam injected gas turbine has the same start-up characteristics as those of a basic gas turbine. But, the time required to speed the former up to a full load operating condition will be prolonged by about 14 minutes because the heat recovery boiler takes a certain amount of time to have its temperature and pressure raised, and the purge and warm-up of the injection system pipelines also take some time.

PERFORMANCE COMPARISON OF SEVERAL TYPES OF PROPULSION PLANTS

A comparison and analysis has been conducted of the main propulsion plant of a medium-sized aircraft carrier when the latter is provided respectively with a nuclear power plant, a steam power plant, a gas turbine power plant and a gas turbine power plant with the capability to provide steam for both injection and aircraft catapults. The data needed for the comparison were mostly obtained through calculations or by proper analogy.

The steam propulsion plant consists of 8 main steam boilers and 4 main geared turbines. For the gas turbine simple cycle version employed are 8 LM2500 engines, 4 reduction gear boxes, three 50 t/h oil-fired boilers (one as stand-by) which serve as a steam source for the catapult operations.

The results of comparison for the four types of propulsion plants are summarized in Table 6.

The data listed in Table 6 show that the simple cycle gas turbine and the steam injected gas turbine have the minimum weight and dimensions. Due to the use of 8 boilers and 4 turbines and the resulting large space the steam power plant occupies 4 main machinery compartments, whose total length is two times that of the gas turbine·power plant. Although in the gas turbine propulsion plant with the capability to provide steam for both injection and aircraft catapults installed are heat recovery boilers, steam/water systems and heat exchangers, etc, yet because of its high specific power and large unit engine output power it can dispense with 4 gas turbines and 2 oil-fired boilers specially installed for aircraft catapult operations as compared with the gas turbine power plant version. Moreover, a significant decrease in its inlet air flow rate, a low exhaust gas temperature and a small exhaust gas volumetric flow rate (see Table 7) also result in a reduced weight of the air intake and the exhaust duct, so that the injected steam gas turbine power plant version enjoys minimum weight and in this respect is comparable with the gas turbine power plant version. As regards overall dimensions, initial capital cost and specific fuel consumption it is even more superior to other versions.

Table 1 Performance Comparison of Three Cycles

	LM5000 simple cycle	LM5000 STIG120	LM5000 ISTIG
power output(kW)	33 210	51 620	~110 000
electric power(%)	36.4	43.2	47~48

Table 2 Gas Turbine Performance

item	unit	gas turbine	steam injected gas turbine
power	horsepower	33 000	49 858
specific fuel consumption	g/hp. hr	181	151.3
steam injection rate	t/hr	0	30.6
overall dimensions	meter	10×3.8×3.4	10×3.8×3.4
weight	ton	32	33.3

Table 3 Main Performance Data of the Heat Recovery Boiler

item	unit	high pressure	low pressure
steam pressure (boiler drum/after superheater)	MPa	6.2/5.8	0.2
steam temperature	℃	370	saturated
steam output	t/h	30.6	13.2
feedwater temperature	℃	104	104
dimensions of boiler proper	meter	4.3×4.1×2	
weight of boiler proper	kg	25 000	

Table 4 The Characteristics of a Three-path Reverse Osmosis-based Sea Water Desalination System

weight	volume	water making capacity.	water quality	energy consumption
t	m	M^3/day	ppm	kJ/kg
73	106	1610	0.107	169.6

Table 5 Main Characteristics of a Steam By-pass Condenser

thermal load	cooling area	volume	weight	overall dimensions
(10^6 · kJ/hr)	(m^2)	(m^3)	(t)	(m)
129	195	6.88	3.92	Φ1.3×4.72

Table 6 Performance Comparison of four Types of Propulsion Plants

ser. №	item	unit	I	II	III	IV
1	propulsion plant type	/	nuclear power	steam power	gas turbine	g. t. with capacity to provide steam for both injection and aircraft catapults
2	catapult steam source	/	shared use	shared use	special equipment needed	shared use
3	number of main plant × unit plant power output	hp	4×45000	4×50000	8×25000	4×48362
4	naval vessel total power	hp	180 000	200 000	200 000	193 448
5	maximum speed	knot	~31	>31	>31	>31
6	total weight of main propulsion plant	t	8100 (including secondary shield)	3000	1300	1410
7	specific weight	kg/hp	45	15	6. 5	7. 29
8	compartment length main/auxiliary	M	2×10+4×15 / 1×11	4×15 / 2×11	2×15 / 4×11	2×16 / 2×11
9	propulsion plant compartment total length	M	91	86	74	54
10	main machinery compartment area saturation degree	hp/m²	109	136	290	263
11	main machinery compartment space saturation degree	hp/m³	11. 5	15	33	30
12	power plant specific fuel consumption (full speed/cruising speed)	gram/hp. hr	/	300/400	195/300	171/233
13	8000 nautical miles (18 knots) main propulsion plant net oil consumption	t	/	7040	5280	3320
14	machinery cold startup preparation time (emergency/normal)	minute	/	30/90	3	3
15	from startup to full power	minute	/	35	3	20
16	propulsion plant exhaust gas volumetric flow rate	m³/hr	/	1 943 448	4 536 832	1 952 044

Table 7 Comparison of Inlet Air and Exhaust Gas Flow Rate for Three Types of Power Plants

	unit	steam power plant	gas turbine	steam injected gas turbine
number of units × inlet air flow rate	(T/h)	8×1436	8×281	4×306
percentage	%	100	195. 5	106. 5
number of units × exhaust gas flow rate	m³/h	8×242 931	8×567 104	4×488 011
percentage	%	100	233. 4	100. 4

From the above it is evident that the gas turbine propulsion plant with the capability to provide steam for both injection and aircraft catapults constitutes an outstandingly superior version among all the others being selected to undergo the foregoing comparison.

CONCLUDING REMARKS

The merits of a steam injected gas turbine plant include high specific power, high efficiency and low investment cost. When used with a cogeneration plant, the STIG unit has as its another outstanding feature the high flexibility in matching electrical power and process heat loads.

In naval propulsion applications the STIG technology retains all its intrinsic advantages. The propulsion system with the capability to provide steam for both injection and aircraft catapults is in a sense the refurbished version of "cogeneration". "The shared use of steam for catapults and injection with the catapults being assigned priority" is in its turn a refurbished version of "the shared use of steam for the production of electrical energy and process heat with process heat being assigned priority". The simultaneous use of steam for aircraft catapults and main propulsion plant makes the STIG technology more suited for use on board an aircraft carrier.

It is obvious that the concept of setting up under a gas turbine Brayton cycle a parallel Rankine regenerative cycle designed for the flexible use of steam for both gas turbine steam injection and aircraft catapults has proved to be very attractive when the said concept is embodied in the aircraft carrier propulsion plant.

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