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Performance and reliability of exhaust gas recovery units for marine engines

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Abstract. Although the marine diesel engine market is dominated by slow-coupled two-stroke engines with a direct coupling system and a crossover system or four-stroke engines with medium or high speeds, equipped with a reversing system, there is a hybrid variant that has always been used by the market in Japan and East Asia, especially by coastal or fishing operators. These are four-stroke slow engines. These types of engines are a specialty specific to the Japanese profile industry, being characterized by a simple and robust construction and fairly long piston strokes. The rated speeds of these motors do not exceed 200 rpm, which allows direct coupling to the propeller, eliminating the need for a reduction system. Compared to equivalent engines on the US or EU market, where medium or high speed four-stroke engines are preferred, the Japanese model has 6-cylinder in-line configurations, and the piston diameters of these engines may vary depending on the need for on market. For example, Akasaka Diesel built engines of the same type using piston diameters ranging from 220 mm to 510 mm, all with in-line 6-cylinder configuration.

Keywords. Exhaust gas recovery, EEDI, WHRS, residual heat.

1. Introduction

If the size of the tanks was more or less the same for 25 years, after World War II, they increased significantly, initially at a slow pace. A typical tank from the T2 range from the time of the Second World War was 162 m long and had a capacity of 16,500 dwt. A modern ultra-large crude carrier (ULCC) can be 400 m long and has a capacity of 500,000 dwt. Several factors have encouraged this massive increase. Hostilities in the Middle East that have disrupted traffic through the Suez Canal have contributed, as has the nationalization of oil refineries in the Middle East. Intense competition between shipowners also played a significant role. Apart from all these considerations, it all comes down to a simple economic advantage: the larger an oil tanker, the cheaper the transportation of crude oil and the more it can contribute to meeting the demands of increasing quantities of oil [1].
Aristotle Onassis and Stavros Niarchos, two Greek shipowners, used this to buy very cheap oil tanks. The expected economic downturn did not materialize for many reasons, including the Marshall Plan, with oil demand rising until 1947, when there was a shortage of tanks on the maritime market. Freight rates have tripled overnight, allowing some shipowners to recoup their investment in a single trip. Ludwig began building universal ships in 1947 and began building large tanks at his shipyards. The

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"Sinclair Petrolore" built by Ludwig in 1955 was a 56,000-ton ship and was not only the largest cargo ship in the world, but also an oil tanker with a self-unloading system, the only one of its kind ever built. It exploded on December 6, 1960 near Brazil - probably due to cargo spills in the double deck - resulting in the largest spill to date with a total of 60,000 tons [2].

Figure 2. The "Sinclair Petrolore" oil tanker[1]

2. Green Attitude oil tanker technical description

The Suez Max oil tanker M/T Green Attitude belonging to the Greek shipping company Aegean Shipping Management was chosen to carry out the study on the performance and reliability of the waste energy recovery units on board a 150,000 dwt oil tanker. It is a new ship, launched in 2018 and has state-of-the-art means to reduce emissions and, consequently, fuel consumption. The construction of the tank is with a double keel. The ship's crew consists of 23 people, the Greek commander, 9 officers (7 Greeks and 2 Filipinos) and unpatented sailors (13 in number), all of Filipino nationality. The vessel is certified in terms of Quality Management in accordance with ISO9001 Standard and IMO Resolution A.741 (18) [3].

Figure 2. M/T Green Attitude oil tanker [3]

The main technical features of the 115.000 dwt oil tanker are the following:

- IMO number: 9769855;
- MMSI: 636018579;
- Flag: Liberia (Monrovia);
- Year of construction: 2018;
- Total length: 249.99 m;
- Length between perpendiculars: 239;
- Construction width: 44 meters;
- Construction draft: 21,30 meters;
- Summer draft: 19.5 meters;
- Deadweight: 115,500 tons;
- Service speed: 18.5 knots;
- Class notations: +100 A1, Double Hull, CSR, ESP, CM, ACS(B, C), LI, *IWS, DSPM4, ECO, ETA, SCM, SERS, VECS, +LMC, UMS, IGS, NAV1, EGCS.

As for the cargo facility, the ship is equipped with three centrifugal pumps with a flow rate of 3000 m^3/hour and a cargo ejector with a capacity of 500 m^3/hour, while the tank is stripped with a pump with a capacity of 200 m^3/hour. There are also 2 cranes on the deck of the ship, each of 15 tons, used to handle the loading and unloading equipment. They are installed in the master couple area of the ship, in both sides. The figure below shows the arrangement of the cargo system on board the M / T "Green Attitude":

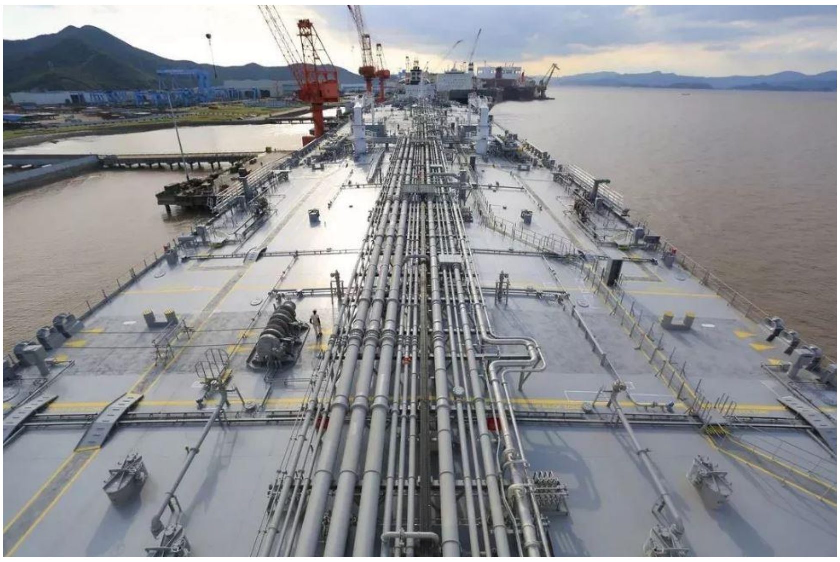

Figure 3. Freight system on the main deck aboard the M/T "Green Attiutude"*Dawn*

3. *M/T Green Attitude* Oil Tanker Maine Engine description

Based on the data presented above, it is possible to proceed to establish the optimal essential parameters of the main engine:

- Engine power (at 90% MCR): 20,650 kW;
- Propeller speed: 106 rpm;
- Cruise speed: 14 knots.

The ME-C engine concept consists of a mechanical-hydraulic system for fuel injection activation. The actuator is electronically controlled by a series of control units that form the complete engine control system. The fuel pressure booster consists of a simple plunger powered by a hydraulic piston activated by the fuel pressure. The fuel pressure is controlled by a proportional valve, which in turn is electronically controlled. The exhaust valve is activated by a light camshaft, actuated by the actuator located at the aft end of the engine. The closing time of the exhaust valve is electronically controlled for low fuel consumption at low load [4].

The chosen engine develops the required power (20,650 kW) at 90% M.C.R. and at a speed of about 106 rpm. It is immediately noticeable that the characteristic parameters of the adopted engine are very close to the previously calculated optimal parameters (the calculated running speed is even higher than originally intended and the relatively high percentage of M.C.R. does not seem to be a rarity in the context of more recent achievements). Therefore, by reducing the speed, speed and percentage of the M.C.R. they will be within the desired limits, so no further adjustments or optimizations are required at this stage.

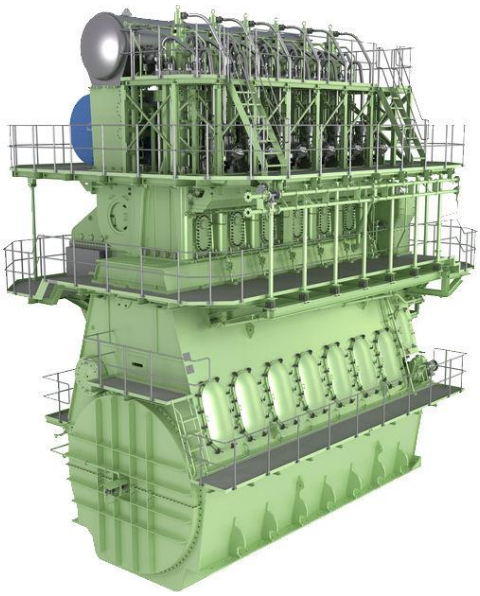

Figure 4. MAN B&W 6G70ME-C9.5 main engine [5]

Fuel system for the MAN B&W 6G70ME-C9.5 main engine which is arranged aboard the MT Green Attitude so that it takes up as little space as possible and provides optimized operation for both solid fuel and marine diesel fuel. From the service tank, the fuel is directed to an electrically operated feed pump with which a pressure of approximately 4 bar can be maintained in the low-pressure part of the fuel circulation system, thus avoiding gasification of the fuel in the exhaust valve box at intervals. temperature applied. The vent valve box is connected to the service tank by an automatic vent valve, which will release any gases present in the fuel path, and which will retain only the liquids. From the low-pressure side of the fuel system, it is driven by an electrically operated circulating pump, which pumps the fuel through a heater and a complete filter located immediately before entering the engine.

The fuel injection is an electronically controlled pressure booster located on the hydraulic cylinder unit (Hydraulic Control Unit - abbreviated HCU), there is one per cylinder, which also contains the actuator for activating the electronically controlled exhaust valve. Cylinder Control Units (CCU) within the engine control system calculate fuel injection timing and exhaust valve activation.

To ensure a sufficient supply of HCU, the capacity of the electrically operated circulating pump is greater than the amount of fuel consumed by the main engine. Excess fuel is recirculated from the engine through the vent/ventilation box. To ensure a constant fuel pressure at the fuel injection pumps during all load regimes applied to the engine, a spring-loaded overflow valve is inserted into the fuel system on the engine. The fuel pressure measured on the engine (at the fuel pump level) must be 7-8 bar, equivalent to a pump pressure of 10 bar.

When the engine is stopped, the fuel pump will continue to run on heavy fuel, already heated, through the fuel system on the engine, thus keeping the fuel pumps heated and the fuel valves ventilated. This automatic circulation of preheated fuel during engine shutdown is the result of the manufacturer's recommendation that constant operation of the engine should be done on heavy fuel. In addition, failure to comply with this recommendation could result in the occurrence of latent deposits of diesel fuel and heavy fuel oil of marginal quality that form incompatible mixtures during switching to another type of fuel or when the ship transits restricted areas.

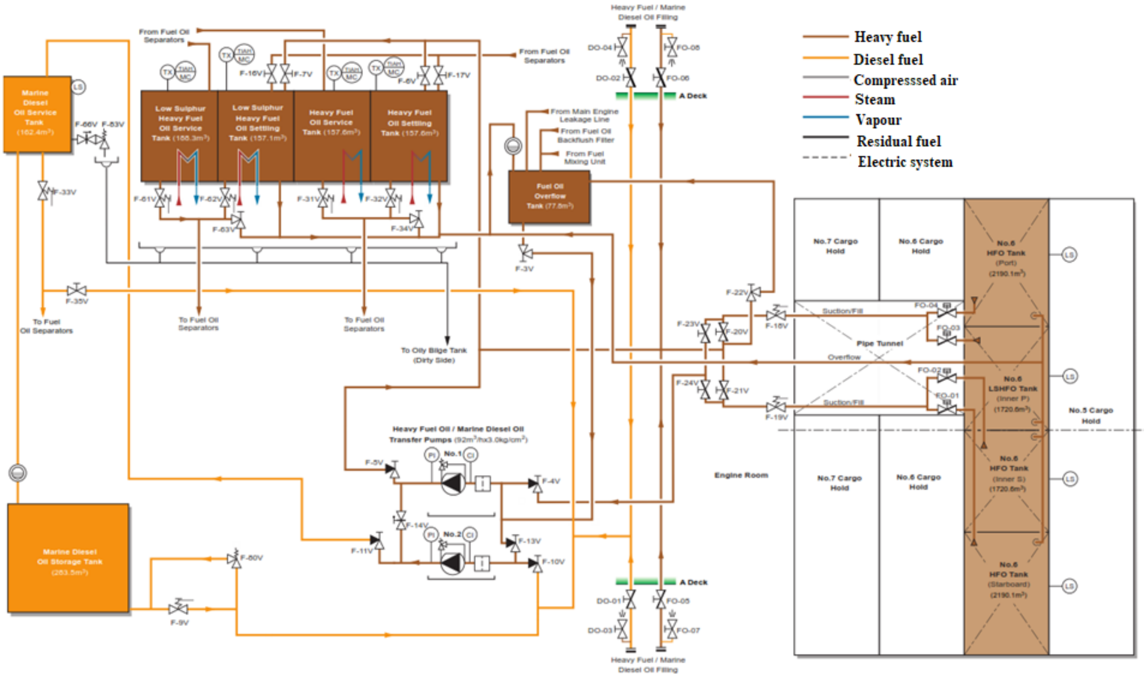

Figure 5. Bunkering and fuel transfer system diagram [8]

4. Waste energy recovery systems used for MAN B&W 6G70ME-C9.5 MAIN ENGINE

Increasing interest in reducing emissions, reducing ship operating costs and the new IMO rules on EEDI call for measures to ensure the optimal use of fuel for the main engines on board ships.

Following the steadily increasing trend of a ship's efficiency since the first oil crisis in 1973, the efficiency of the main engines of ships has increased considerably, currently the efficiency in terms of fuel consumption is about 50%. This efficiency has led, among many other positive things, to reduced SFOC emissions, but also to a much lower exhaust gas temperature after they pass through the turbochargers of the main engine [5].

The primary source of residual energy from a main engine is the exhaust, dissipated gas, which holds over 50% of the share of residual heat, from about 25% of total fuel consumption. In the case of standard high-efficiency main engines, the relative temperature of the exhaust gas is relatively low after turbochargers, but high enough to produce the required amount of steam for heating the vessel by means of a type boiler[6].

Today there are different types of WHRS that are available for direct fitting on board the ship. Depending on the level of complexity and the acceptability of the owner of the ship, but also of the shipyard that builds the ship, as well as the consumption of electricity on board the ship, shipbuilders can opt for the following types of systems:

- ST-PT - (Steam Turbine - PT Generator - Steam Turbine - Turbine Driven Generator Unit) - This consists of power/energy turbine, steam turbine and steam turbine power generator unit with single or double pressure system;
- STG - (Steam Turbine Generator - Steam Turbine Generator Unit) - This unit consists of steam turbine, drive system and power generation unit with single or double pressure system;

- PTG - (Power Gas Turbine - Turbine Power Generation Unit) - Power turbine system, drive system and generator unit).

In particular, for oil tanker ship-type projects, WHRS has proven to be very useful, with a significant effect on CO_2 emissions, but these types of systems are increasingly being used on board other types of ships as well. reducing fuel consumption, the ship's EEDI and total shipboard emissions [7][8].

The use of a TCS-PTG WHRS system has been shown to have a power recovery range of 3 to 5%, depending on the size of the main engine on board.

There are currently several versions of the TCS-PTG system, which is based on the TCR series model, and their power values are:

- TCS-PTG18 - 1070 kW;
- TCS-PTG20 - 1560 kW;
- TCS-PTG22 - 2700 kW.

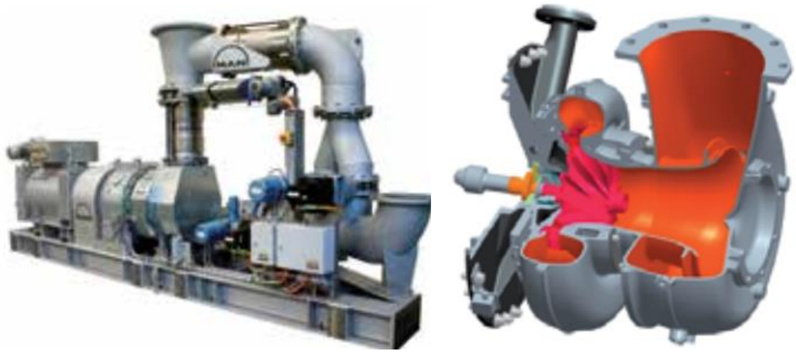

Figure 6. WHRS TCS-PTG systems developed by MAN Diesel & Turbo[8]

5. Reliability of Residual Heat Recovery Units

The quality of products and services is the basic indicator of an industry or economy. As reliability, along with other indicators, is a component of quality, it must be in the attention of all the factors that determine the good of society. Although the notion is very old - it appeared with the technique - it is feasible that the theory was formed in the last decades and is in a continuous development. The concept of age and new discipline, the theory of reliability is an interdisciplinary science that refers to a wide range of problems in all aspects of the existence of products (projectors, fittings).

The reliability of a product is determined by its design (projectors) when its structure is established and its dimensions are measured. Its reliability is ensured in the manufacturing process by the correct choice of technological processes and equipment, by respecting the manufacturing regimes and conditions of the factory and by strict quality control. Feasibility is maintained through the use of adequate methods of preservation, transport, commissioning and operation. Qualitative analysis of reliability provides relevant information to the analysis in which it is reflected, in the functioning of the analytical entity, the different ways of the other components. Qualitative analysis of the feasibility analysis is:

- the analysis of the means of failures and of the effects of these failures by which it identifies the defects and evaluates the consequences of this on the functioning of the entity;
- organization and graphical representation of the information resulting from the previous analysis in the form of a logical scheme (block diagram or tree of defects).

Quantitative Approach - Feasibility is the probability that the system will perform its functions for which it has been conceived and realized, with a certain and unambiguous performance, without delay. The quantitative approach to reliability is that it is objectively quantified, in the form of numerical indicators, of the level of reliability of the entities established for:

- comparison of two or more solutions from the point of view of the desired performance;
- demonstration of the classification of the values of the feasibility indicators within certain imposed limits, in the points of interface with other entities (installations, electric lines);
- detection of weak links within the analyzed entities;

elimination of some indicators of guarantees included in the offers and contracts.

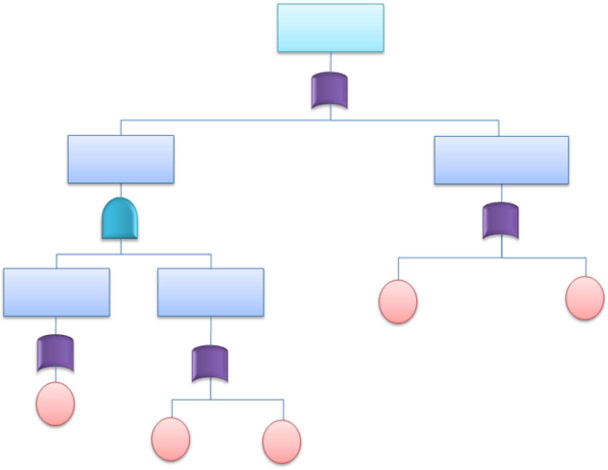

Figure 7. Model of tree analysis of faults

Calculating the reliability of non-repairable components of the WHRS system - Irreparable elements are characterized by the T_f indicator - the operating time to the fault, expressed in the form of a variable by:

- reliability function:

$$R(t) = 1 - F(t) \tag{1.1}$$

- non-reliability function:

$$F(t) = P(T_f \leq t) \tag{1.2}$$

- frequency function (distribution density):

$$f(t) = \frac{dF(t)}{dt} = \frac{P[t < T_f < t + dt]}{dt} \tag{1.3}$$

- failure rate:

$$\lambda(t) = P[t < T_f < t + dt, T_f > t] = \frac{f(t)}{1 - F(t)} \tag{1.4}$$

- functioning mean duration:

$$M[T_f] = \int_0^\infty t \cdot f(t)dt \tag{1.5}$$

In order to calculate the feasibility indicators of a system, it is necessary to know, in addition to the feasibility indicators and the component elements, the structure of the system. For the application of this category of methods, the structure of the system is expressed in the form of the functions of the structure or the functions of the feasibility. The feasibility function has the general formula:

$$R_s(t) = f(R_i(t)) \tag{1.6}$$

where:
- Rs (t) - is the probability of functioning of the system at time t;
- Ri (t) - is the probability of the function of the element and the moment t.

In the case of serial systems as well as the WHRS system analyzed, considering that it consists of a fixed number of independent elements, the formula for calculating its reliability is as follows:

$$R(t) = \prod_{i=1}^{n} R_i(t) \tag{1.7}$$

Otherwise written as:

$$F_s(t) = 1 - \prod_{i=1}^{n} (1 - F_i(t)) \tag{1.8}$$

On the basis of the above, the links between the other indicators of the system and the system will be based on those elements. In the case of serial systems, the distribution of the operating time preserves its exponentiality, the intensity of the system malfunctions being equal to the sum of the intensity of the faults. It is considered that the WHRS system for the recovery of residual heat is a system consisting of m = 50 identical subsystems, each one of them can be calculate with the following:

- Probability of system survival: Rs (22);
- Average operating time of the system: M [Tf];
- Intensity of a defect in an element of the system (λ_e) and of the subsystem if it consists of n = 60 of the identical elements;
- The value of the stock should be Rs (22) to be 0.85.

The following formula is used to calculate the probability of survival:

$$R_s = R_i^m = 0.985^{50} = 0.46969 \tag{1.9}$$

$$\lambda_s = - (\ln R)/t = - \ln 0.46969 = 3.77841\cdot 10\text{-}^{6}\ [h^{-1}] \tag{1.10}$$

Calculation of the average operating time of the system:

$$M[T_f] = 1 / \lambda_s = 1 / (3.7781\cdot 10\text{-}^{6}\ [h^{-1}]) = 264661.59\ [h] \approx 30 \text{ years} \tag{1.11}$$

Defect intensity calculation:

$$\lambda_e = \lambda_s / (m\cdot n) = 3.7781\cdot 10\text{-}^{6} / 50\cdot 60 = 1.25937\cdot 10^{-9}\ [h^{-1}] \tag{1.12}$$

Table 1: Calculation ratios for reliability indicators

Indicator	**General case** $R_i(t) = 1 - F_i(t) = e^{-\int_0^t \lambda_i(t)dt}$	**Formula for the case of exponential repartition** $R_i(t) = e^{-\sum_{i=1}^{n} \lambda_i(t)}$
$R_s(t)$	$R_s(t) = \prod_{i=1}^{n} e^{-\int_0^t \lambda_i(t)dt} =$ $= e^{-\int_0^t \sum_{i=1}^{n} \lambda(t)dt}$	$R_s(t) = e^{-\sum_{i=1}^{n} \lambda_i(t)}$ $R_s(t) = e^{-n\lambda t}$ **for** $\lambda_1(t) = \lambda_2(t) = \ldots = \lambda_n(t) = \lambda$
$M[T_f]$	$M[T_f] = \int_0^{\infty} t \cdot f_s(t)dt =$ $= \int_0^{\infty} R_s(t)dt$	$M[T_f] = \frac{1}{\sum_{i=1}^{n} \lambda_i}$ $M[T_f] = \frac{1}{n\lambda}$ **for** $\lambda_1 = \lambda_2 = \ldots \lambda_n = \lambda$
$\lambda_s(t)$	$\lambda_s(t) = \frac{f_s(t)}{1 - F_s(t)}$	$\lambda_s(t) = \sum_{i=1}^{n} \lambda_i$ $\lambda_s(t) = n\lambda$ **for** $\lambda_1 = \lambda_2 = \ldots = \lambda_n = \lambda$

The λ_s value calculation is based on the formula:

$$\Lambda_s = m \quad \cdot n \cdot \lambda_e' = -\ln R_s / t \tag{1.13}$$

$$\lambda_e' = -\ln R_s / (m \cdot n \cdot t) = \ln 0.85 / (50 \cdot 60 \cdot 2 \cdot 10^5) = 2.70865 \cdot 10^{-10}\ [h^{-1}] \tag{1.14}$$

If it is considered that the WHRS system for the recovery of residual heat is parallel, then the calculation of the reliability will be based on a different set of formulas. In particular, the parallel system is out of order if it fails to function properly. If noted:

$$Q_s(t) = 1 - R_s(t) = F_s(t) \tag{1.15}$$

Then:

$$Q_s(t) = \prod_{i=1}^{n} Q_i(t) = \prod_{i=1}^{t} F_i(t) \tag{1.16}$$

Thus:

$$F_s(t) = 1 - \prod_{i=1}^{t} F_i(t) \tag{1.17}$$

On the basis of the previous relations, of the serial and parallel systems, it is possible to deduce the generalized relations for the serial-parallel decomposable systems. For the decomposable system of the series, as can be considered the WHRS system for the recovery of residual heat, consisting of "m" subsystems (of groups of 1). The reliability of the system is:

$$R_s(t) = \prod_{j=1}^{m} [1 - \prod_{i=1}^{nj} (1 - R_{ji}(t)] \tag{1.18}$$

where Rji (t) is the probability of functioning of the element i of the subsystem (group of defects) j.

For the decomposable parallel system consisting of "m" subsystems (minimal pathways) tied in a parallel system, each having n_i, i = 1, 2,…, nm elements:

$$R_s(t) = 1 - \prod_{j=1}^{m} [1 - \prod_{i=1}^{nj} (1 - R_{ji}(t)] \tag{1.19}$$

Table 2: Calculation Methods for Parallel Systems Indicators

Elemente indicator	**General case** $R_i(t) = e^{-\int_0^t \lambda_i(t)dt}$	**Exponential repartition case** $R_i(t) = e^{-\lambda_i t}$
$R_s(t)$	$R_s(t) = 1 - \prod_{i=1}^{n} [1 - e^{\int_0^t \lambda_i(t)dt}$	$R_s(t) = 1 - \prod_{i=1}^{n} [1 - e^{-\lambda_i t}]$ $R_s(t) = 1 - [1 - e^{-\lambda t}]^n$ **for** $\lambda_1 = \lambda_2 = \ldots \lambda_3 = \lambda_n = \lambda$
$M[T_f]$	$M[T_f] = \int_0^{\infty} R_s(t)dt$	$M[T_f] = \sum_{i=1}^{n} \frac{1}{n\lambda}$ **for** $\lambda_1 = \lambda_2 = \ldots \lambda_n = \lambda$ $M[T_f] = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \frac{1}{\lambda_1 + \lambda_2}; n = 2$ $M[T_f] = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} + \frac{1}{\lambda_3} - \frac{1}{\lambda_1 + \lambda_2} -$ $- \frac{1}{\lambda_1 + \lambda_3} - \frac{1}{\lambda_2 + \lambda_3}; n = 3$

5. Conclusions

In recent years, there has been a large amount of residual heat released into the environment, such as exhaust fumes from turbines and internal combustion engines, residual heat from industrial installations, which lead to environmental pollution. In addition, there are also abundant resources of solar and geothermal energy. These heat sources are classified as low temperature thermal energy. Therefore, more and more attention has been paid to the use of waste heat for its potential in reducing fossil fuel consumption and mitigating environmental problems.

The recovery of waste energy is a growing concern for building developers, especially at European level, and in this field researchers have intensively studied the development potential of tube heat recuperators. As in the naval field, increasing energy efficiency and the use of renewable energy sources in the building sector is a priority.

Energy consumption for buildings today accounts for around 42% of final energy consumption in the European Union with a high potential for energy recovery of around 22% in the short term. Today, 35% of EU buildings are over 50 years old. By improving the energy efficiency of buildings, the EU's total energy consumption could be reduced by up to 56% and CO2 emissions by around 5%.

This issue of heat recovery from human activities is increasingly seen from the point of view of environmental protection against "thermal pollution". Energy saving and environmental protection require the collection of heat from unconventional energy sources or thermal waste for use in various technological purposes. Thermal tube recuperators are the most widespread application of these devices in the industrial, commercial or domestic field. The thermal tube is a low temperature gradient heat exchanger that has found numerous applications in various fields of human activity immediately after the first publication, in 1964, of the principle of operation by researchers at the Los Alamos Laboratory (USA). Since then, new research directions have opened up and huge technological advances have been made in the research and improvement of the device. The first research was carried out in the national laboratories specialized in the elaboration of the top technologies in the space and nuclear fields in the states with a scientific and economic potential: USA, Great Britain, France, Germany, Italy. Romania is among the countries in Eastern Europe where the technology of the thermal tube has found a favorable echo.

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