ADVANCED TECHNOLOGIES FOR WASTE HEAT RECOVERY IN INTERNAL COMBUSTION ENGINES

M.Sc. Milkov N., Assoc.Prof. PhD. Evtimov T., Ass. Prof. PhD. Plamen P.
Faculty of Transport – Technical University of Sofia, Bulgaria
nikolay.milkov@tu-sofia.com

Abstract: *The escalating fuel price and carbon dioxide legislation have renewed the interest in the methods of increasing engine thermal efficiency beyond in-cylinder techniques. The aim of this study is to review the latest technologies of waste heat recovery of exhaust gases in internal combustion engines. These include turbocompounding systems, thermoelectric generators, thermoacoustic systems and closed-loop thermodynamic cycles based on Stirling, Ericsson and Rankine cycles. A number of studies revealed that Rankine cycle is the most perspective waste heat recovery system due to its higher thermal efficiency. Finally, the components of the Rankine cycle (working fluid, evaporator and expander) were studied in detail.*

Keywords: WASTE HEAT RECOVERY, RANKINE CYCLE, INTERNAL COMBUSTION ENGINES, CO_2 EMISSIONS.

1. Introduction

An analysis of the European Commission shows that over 80% of the greenhouse gases in the atmosphere are composed of carbon dioxide. Over 25% of the carbon dioxide in the atmosphere is produced by transport, due to the burning of fossil fuels in internal combustion engines, see Fig. 1.

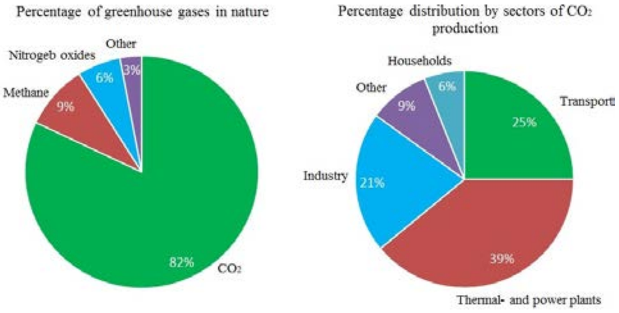

Fig. 1 *Percentage of greenhouse in nature and distribution by sectors.*

For this reason, the European Commission introduced legislation on carbon dioxide emissions produced by automobiles [1]. In 2020, emissions of carbon dioxide produced by light-duty vehicles must not exceed 95g CO_2/km, compared to the emissions produced in 1990 which is a reduction by 30% (Fig. 2).

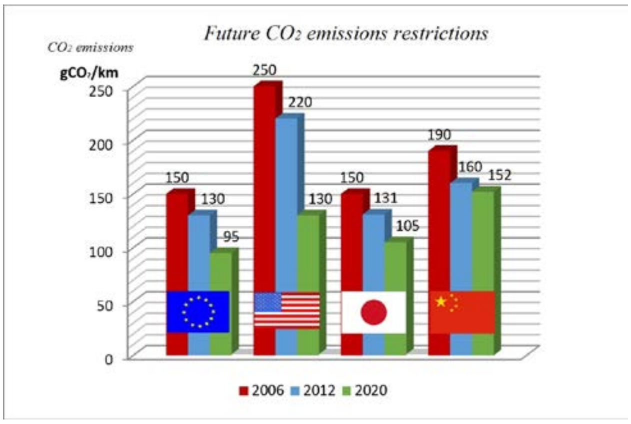

Fig. 2 *Future CO_2 emission legislation.*

In modern engines the overall efficiency is not more than 40%. However, most of the time engines operate with much lower efficiency than their maximum. In other words, a significant part of the energy released by the fuel in internal combustion engines is lost. That energy is lost in a form of heat in the exhaust and cooling system. Usually, the exhaust gases have higher energy than cooling system. The heat energy contained in the exhaust gases depends on the operating point of the internal combustion engine. Milkov et. all [2] estimated this energy to be within the range of 25% to 65%. In the same engine the heat energy in the cooling system is within the range of 11% to 35%. There are two ways of increasing the overall efficiency, of reducing the fuel consumption and carbon dioxide emissions, respectively: by improving the working processes and waste heat recovery.

In spite of the existence of modern technologies for improving the working processes in internal combustion engines such as turbocharger systems, direct fuel injection, downsizing, low temperature combustion processes (CAI and HCCI), variable compression ratio, etc., the future requirements for internal combustion engines will be difficult to be met [3, 4].

For that reason waste heat recovery is a good way of increasing the overall engine efficiency, reducing the fuel consumption and CO_2 emissions.

2. State-of-the-art of waste heat recovery systems

Research has revealed that some advanced technologies can be applied to further improve waste heat recovery efficiency. Several technologies have been studied such as turbocompounding systems thermodynamic cycles (Rankine, Stirling, Ericsson and etc.), thermoelectric generators and thermoacoustic systems.

2.1 Turbocompounding systems

Over the last decade turbocompounding has been developed as an additional waste heat recovery system. Systems of this type convert part of the exhaust gas energy into mechanical or electrical energy, therefore they are of two types: mechanical and electrical turbocompounding. In mechanical turbocompounding the turbine shaft is mechanically connected to the engine crankshaft and the energy of the system is added directly to the engine output (Fig.3.)

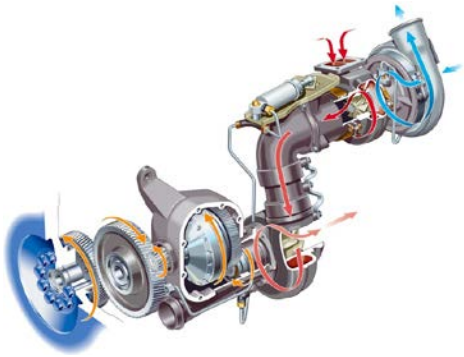

Fig. 3 *Mechanical turbocompound.*

In electric turbocompounding the turbine shaft is connected to a generator. In this case the energy is converted into electricity. The electrical turbocompunding can be developed without additional turbine. In this case the generator is mounted directly onto the turbocharger's shaft. (Fig.4.)

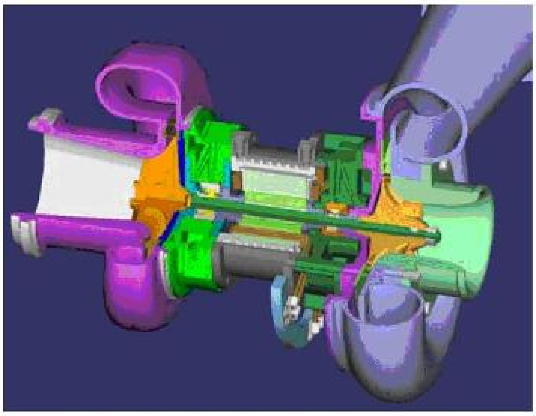

Fig. 4 *Electric turbocompaunding.*

The disadvantage of such turbocompounding which includes an additional turbine is that the second turbine creates an additional backpressure in the exhaust system and adversely affects the gas-exchange process.

According to this study [5] the benefits of the implementation of mechanical turbocompounding are:

- Increase in attained power by 10-11%,
- Torque increase about 11%,
- Reduction in fuel consumption by 5-11%.

2.2 Thermoelectric generators

Thermoelectric generators use the properties of some materials which because of the effect of temperature difference generate voltage (effect Seebeck).

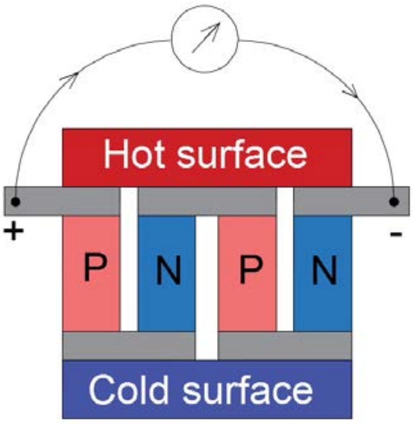

Fig. 5 *Thermoelectric generators.*

The principle of operation is as follows: the thermoelectric element is placed between two surfaces called hot and cold. The difference in temperature causes changes in the core of the thermoelectric material, which converts thermal energy into electricity.

The efficiency of the thermoelectric generators depends on the material and the efficiency of heat exchange between the exhaust gases and the hot part of the generator. At this point it does not exceed 5%.

Their advantage is that they do not create noise and vibration and have no moving parts or create minimal resistance in the exhaust system of internal combustion engines. However, due to their low efficiency, high cost and heavy weight at this stage they have not been used in series production engines.

2.3. Thermoacoustic systems

The thermoacoustic effect is the interaction between the temperature, density and pressure difference of sound waves. Thermoacoustic engines are thermoacoustic devices that use high amplitude sound waves to transfer heat from one place to another, or vice versa, use heat to produce high amplitude sound waves. Generally thermoacoustic engines can be divided into two types:

- constant wave thermoacoustic systems (Fig.6.);
- variable wave thermoacoustic systems (called "running" waves).

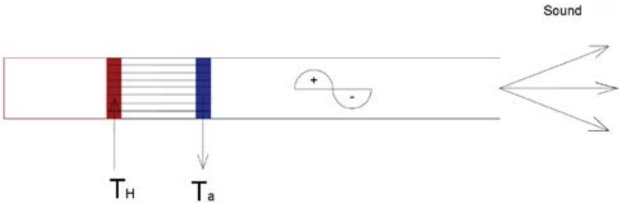

Fig. 6 *Thermoacoustic system.*

Thermoacoustic devices are suitable for heat recovery, as they can operate with a low heat source. Technological thermoacoustic devices have the advantage that they have no moving parts, which makes them attractive for applications where reliability is important.

Thermoacoustic engines have some disadvantages such as:

- Low power and large size;
- Use fluids with high viscosity;
- Low efficiency compared to other devices;
- Complex construction and high cost of production.

2.4. Closed-loop thermodynamic cycles

2.4.1. Stirling cycle

The Closed-loop thermodynamic cycle of Stirling was patented by Dr. Robert Stirling in 1816. This closed thermodynamic cycle operates with different types of fluids. The most commonly used ones are air, hydrogen or helium. The working process in the Stirling cycle occurs in four stages (Fig.7.):

1-2. T = constant expansion (heat transfer from the external source)

2-3. V = constant regeneration (internal heat transfer from the working fluid to the regenerator)

3-4. T = constant compression (heat rejection to the external sink)

4-1. V = constant regeneration (internal heat transfer from the regenerator back to the working fluid)

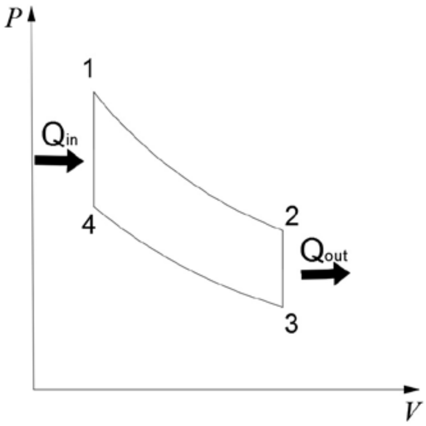

Fig. 7 *Working process of Stirling cycle in P-V diagram.*

A study of Thombare at all. [6] shows that the Stirling cycle has high efficiency when the cycle operates with low heat source. According to that study suitable fluids for this cycle are air and helium.

A study of Igobo at all. [7] shows that the thermodynamic cycles of Stirling are suitable for waste heat recovery in internal combustion engines, but there is still a lot of research to be done in order to improve their effectiveness as a waste heat recovery system.

2.4.2 Erickson cycle

The Ericsson cycle is similar to the Stirling cycle, except that the two constant-volume processes are replaced by two constant-pressure processes. The working process in the Erickson cycle occurs in four stages (Fig.8):

1-2. Isobaric heating of the working fluid - a process in which the temperature of the working fluid increases at constant pressure.

2-3. Isothermal expansion - a process in which the fluid expands at constant temperature.

3-4. Isobaric cooling - a process in which the liquid temperature decreases at constant pressure.

4-1. Isothermal compression - a process in which the fluid is compressed at constant temperature.

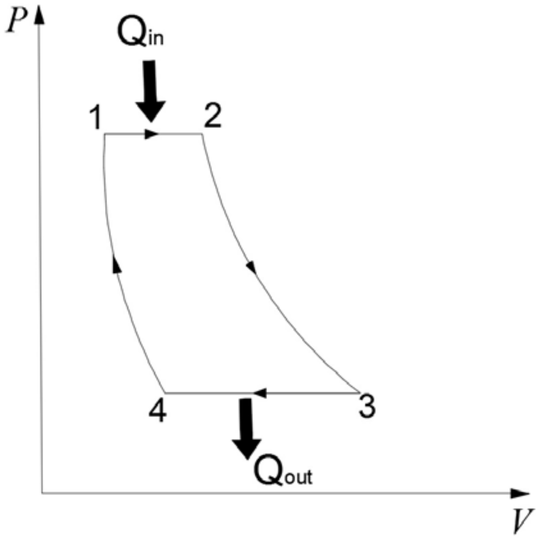

Fig. 8 *Working process of Erickson cycle in PV diagram.*

2.4.3 Rankine cycle

The Rankine cycle is a closed-loop thermodynamic cycle which converts heat into mechanical power. The mechanical power can be used to perform mechanical work or to produce electricity. Separately, this cycle is widely used in the production of electricity by thermal power plants.

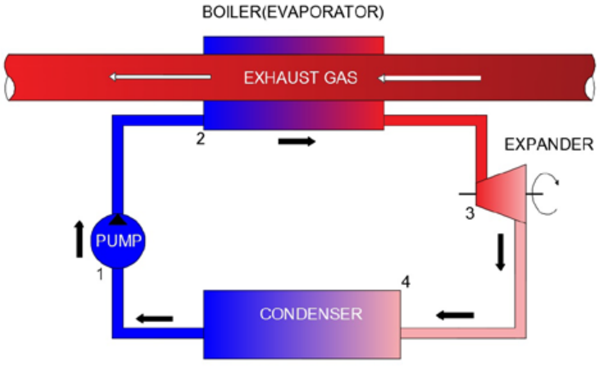

Fig. 9 *Rankine cycle.*

The system consists of the following elements: working fluid, pump, boiler (evaporator), expander and condenser (Fig.9). The ideal Rankine cycle presented in the T-S diagram (Fig.10) consists of the following processes:

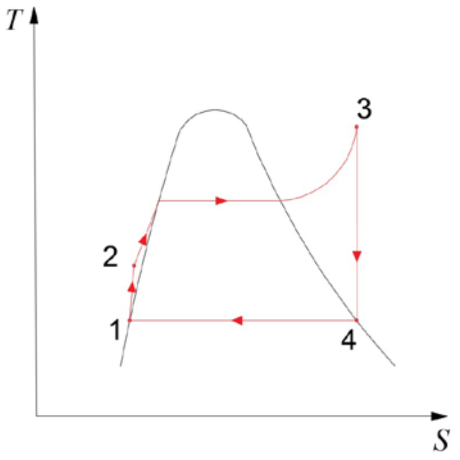

Fig. 10 *Closed-loop Rankine cycle process*

1-2 Isentropic compression in the pump;
2-3 Working fluid heating and evaporation in the boiler;
3-4 Isentropic expansion in the turbine;
4-1 Working fluid cooling in the condenser.

The Rankine cycle efficiency depends on: the working fluid, boiler (evaporator), expander, condenser and working fluids operating parameters (mass flow rate and pressure).

Table 1 presents the results of research on the waste heat recovery system based on the Rankine cycle.

Table 1: *Review of researches on waste heat recovery system based on Rankine cycle*

Author	Working fluid	Expander	Conclusions
Kang S. (2012) [8]	R245fa	Turbine	The maximum average cycle, turbine efficiencies, and electric power were found to be 5.22%, 78.7% and 32.7 kW, respectively.
Hountalas D. at al. (2011)[9]	Organic fluids and water	Piston machine	The maximum improvement in BSFC was observed in the case of the organic Rankine cycle(ORC) and is ~11.3% when both EGR and CAC heat amounts are utilized. The corresponding value for steam is 9%.
Weerasinghe W. (2010)[10]	-	-	A numerical study shown that waste heat recovery system based on steam Rankine cycle can offer substantial gains in fuel economy, potentially in the order of 20%.
Katsanos C. (2012)[11]	Water and the refrigerant R245ca	Turbine	Water - BSFC improvement by 6.1% to 7.5%; R245ca - BSFC improvement by 10.2% to 8.4%
Barrieu E. (2013)[12]	Water and ethanol	-	The order of magnitude of the saved fuel can be estimated at 4 to 10% depending on the usage and the system optimization.
Espinosa N. (2011)[13]	Ethanol and water, R245fa, fluorinol mixtures	-	The challenge for waste heat recovery techniques remains the heat rejection as Rankine cycle system efficiencies are quite low (10-15 %). The R245fa shown best results in this study.

Leduc P. (2013)[14]	Water	Piston machine	At medium engine power, corresponding to highway vehicle use, Rankine system produces about 1 kW of mechanical power.
Chen Y. (2012)[15]	R123	Turbine	The peak net power output and thermal efficiency of Rankine cycle are 15.087 kW and 13.38 %. The diesel engine power increases by 6.17 %.
Capata R. (2014)[16]	R-134a, R245fa and water	Turbine	The smallest turbine shown best results when the working fluid is R134a. The greatest amount of power is when the R245fa is used as working fluid with the largest turbine.
Yang K. (2014)[17]	R416A	-	When the degree of superheat is 40 K, engine torque is 300 N·m, and engine speed is 1900 r/min, the exergy efficiency of the ORC waste heat recovery system reaches its maximum of 54.60%.
Dolz V. (2011)[18]	Organic fluids and water	Turbine	Water Rankine cycle BSFC reduction is between 8.5 - 8.8%.
Serrano J. (2011)[19]	Water	Turbine	Water Rankine cycle achieves about 15% increment in the global mechanical power.
Boretti A. (2011)[20]	R245fa	Turbine	ORC increase the fuel efficiency by 5.1% with maximum improvement of 8.2% when the engine is operating steady state.
Roy J. (2010)[21]	R-12, R-123 and R-134a	Turbine	R-12 - RC efficiency is 12.09%; R-123- RC efficiency is 25.30%; R-134a-RC efficiency is 15.53%.
Yu G. (2012)[22]	R245fa	Turbine	The ORC system gets relatively high power (15.5 kW, 14.5 kW and 13.7 kW) and efficiencies (9.1%, 9.2% and 9.4%) under conditions 1, 2 and 3.
Zhang H. (2012)[23]	R245fa and R134a	Two turbines	In the peak effective thermal efficiency region, the augmentation proportion of the effective power for the combined system is the lowest, at 14–16%, but is highest in the small-load and high-speed region where the augmentation proportion is 38–43%.

The literature review revealed that the exhaust waste heat recovery systems based on the Rankine cycle provide high efficiency. The system efficiency can reach 15% to 20% which means that the engine efficiency improvement is by 10% to 12%. Therefore, the construction of the Rankine cycle will be presented in greater details.

3. Features of the Rankine cycle

3.1 Working fluid

In the development of the Rankine cycle waste heat recovery system, one of the most important steps is the selection of the working fluid because its operating properties have a great influence on the efficiency, size and design. A number of fluids have been studied such as: water, ethanol, benzene, organic fluids and etc. Water provides high efficiency in the case of a high temperature heat source while organic fluids are more efficient in the case of a low temperature heat source.

The working fluids used in the Rankine cycle can be divided into three groups according to the slope of the condensation line in *T-S* diagram: wet, dry and isentropic [24].

The temperature of the heat source is the main criterion in selecting the working fluid (Fig.11).

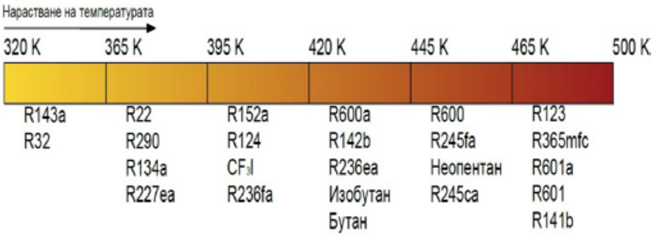

Fig. 11 *Organic fluids classified by the temperature of the heat source*

The results of some studies of various fluids used as the working fluids of the Rankine cycle are listed in Table 2

Table 2: *Review of research of the various working fluids*

Author	Studied working fluids	Criteria / Methodology	Recommended
Punov at al. (2015) [25]	Water, ethanol, R245fa and R134a	Theoretical study of the Rankine cycle	Water as the working fluid provides the highest Rankine cycle output power and efficiency
Chen at al. (2010) [26]	35 different fluids	Review and analysis of working fluid selection criteria for sub- and supercritical ORCs	R32, R125 and R143a - supercritical ORCs; R141b, R123, R21, R245ca, R245fa, R236ea and R142b - subcritical ORCs; R134a, R290, R124, R227ea, R218 - for both.
Hung at al. (2010) [27]	11 different fluids	-	The fluids with best results are the isentropic type fluids.
Lakew at al. (2010) [28]	R134a, R123, R227ea, R245fa, R290 and n-pentane	-	R227ea, R245fa and n-pentane
Mikielewicz at al. (2010) [29]	20 different fluids	Criteria for sub- and supercritical ORCs	Ethanol, R123 and R141b
Fernandez at al. (2011) [30]	Siloxanes	Criteria for sub- and supercritical ORCs	MM and MDM
Guo at al. (2011) [31]	13 different fluids	Thermodynamics and techno-economic evaluation of the transcritical Rankine cycle	R125 best fluid to the temperature of 90 °C of the heat source, R32 and R143a to 100 °C
Guo at al. (2011)	27 different fluids	-	E170, R600 and R141b

[32]			
Datla at al. (2012) [33]	11 different fluids	-	n-pentane
Gao at al. (2012) [34]	18 different fluids	Net power exergetic efficiency, size setting of the regulator and of the required heat exchanger (evaporator and condenser) are evaluated for the selection	R152a and R143a
He и др. (2012) [35]	22 different fluids	-	R114, R245fa, R123, R601a, n-pentane, R141b and R113
Heberle at al. (2012) [36]	mixture of isobutane / isopentane and R227ea / R245fa	-	The mixture of R227ea / R245fa is recommended
Vidhi at al. (2012) [37]	7 different fluids	-	R134a

3.2 Expander

Another essential element of the Rankine cycle is the expansion machine. The expansion machine is the element of the system which converts thermal energy contained in the fluid into mechanical work. Expansion machines are of several types: turbine, reciprocating piston machine, screw, scroll and vane [24].

Two types of expansion machines are most widely used – turbines and piston machines. A higher specific power is a typical advantage of turbines but they can't provide high efficiency for low power systems. Piston machines are preferred in automotive application due to their low speed, compatible with the engine speed.

Table 3 presents the results of research of different expander machines.

Table 3: *Review of research of the different expander machines.*

Author	Studied expander machine	Efficiency (%)	Power (kW)
Yamamoto at al.[38]	Radial-inflow turbine	48	0.15
Nguyen at al.[39]	Radial-inflow turbine	49.8	1.44
Yagoub at al.[40]	Radial-inflow turbine	85, 40	1.50
Inoue at al. [41]	Radial-inflow turbine	70-85	5-10
Kang[8]	Radial-inflow turbine	78.7	32.7
Pei at al. [42]	Radial-inflow turbine	65	1.36
Li at al. [43]	Radial-inflow turbine	68	2.40
Zanelli at al. [44]	Scroll expander	63-65	1-3.5
Mathias at al.[45]	Scroll expander	67,81,83	1.2, 1.38, 1.75
Peterson at al. [46]	Scroll expander	45-50	0.14-0.24
Wang at al. [47]	Scroll expander	70-77	0.5-0.8
Saitoh at al.[48]	Scroll expander	65	0-0.46
Kim at al. [49]	Scroll expander	33.8	11-12
Manolakos at al.[50]	Scroll expander	10-65	0.35-2
Guangbin at al.[51]	Scroll expander	-	0.4-1.1
Wang at al. [52]	Screw expander	26-40	0.5-3
Smith at al. [53]	Screw expander	48-76	6-15.5
Baek at al.[54]	Reciprocating piston expander	70.5	24.35
Zhang at al.[55]	Reciprocating piston expander	62	-
Mohd at al.[56]	Rotary vane expander	43-48	0.025-0.032
Yang at al. [57]	Rotary vane expander	17.8-23	-

3.3 Boiler (Evaporator)

Heat exchangers are devices where heat transfer from one medium to another occurs. In waste heat recovery systems based on the Rankine cycle transfer of heat from the exhaust gas to the working fluid is carried out in a heat exchanger called the evaporator. The object of a number of studies is to establish the type of heat exchanger which is most suitable for application in the Rankine cycle. Heat exchangers can be classified into many groups, because of their diversity. One of the methods of their classification is by the movement of the fluids: co-current and countercurrent heat exchangers (Fig.12.)

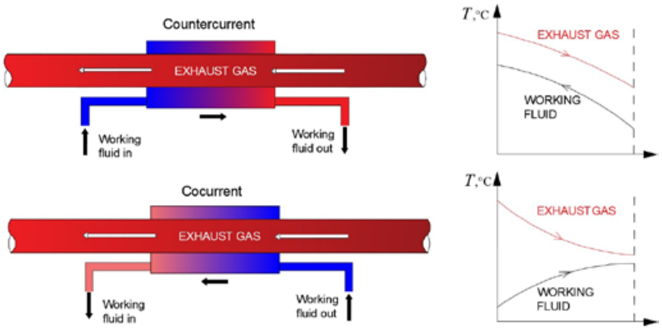

Fig. 12 *Co-current and countercurrent heat exchangers.*

Table 4 presents the results of research of different types of evaporators.

Table 4*: Review of research of the different types of heat exchangers.*

Author	Heat exchanger type	Methodology	Conclusions
Pandiyarajan at al.[58]	Shell and finned tube	Experimental study	Nearly 10–15% of total heat is recovered
Lee at al.[59]	Small fin-tube	Experimental and Taguchi method	The heat exchanger that had maximum effectiveness was not necessarily the

			optimum design.
Zhang at al.[60]	Finned tube	Mathematical ORC modeling	The overall heat transfer rate of the evaporator increases with engine power and reaches 70.4 kW at the rated power point.
Ghazikhani at al. [61]	Simple double pipe	Experimental and exergy analysis	12% reduction in BSFC
Wang at al.[62]	Multi-coil helical	Experimental and ORC numerical simulation	Total fuel saving was up to 34% under 2000 rpm and 75 Nm
Hossain at al. [63]	Shell and tube	Experimental and CFD modeling	Improving the effectiveness of heat exchanger from 0.44 to 0.76 by optimization design
Bari at al. [64]	Shell and tube	Experimental and CFD modeling	An additional 23.7% power improvement achieved by using water as the working fluid

4. Conclusions

On the basis of the review of the methods of increasing the overall engine efficiency, of reducing the fuel consumption and emissions CO_2 from internal combustion engines, the following conclusions can be drawn:

- Although there are modern systems of improving the working processes in internal combustion engines the future requirements for reducing CO_2 are difficult to be achieved;

- Since 60% of the energy in the internal combustion engine is lost as heat the waste heat recovery system is a good way of increasing the overall engine efficiency;

- The literature review revealed that the exhaust waste heat recovery system based on the Rankine cycle provides higher efficiency than others. The system efficiency can reach 15% to 20% which means that the engine efficiency improvement is between 10% and 12%.

- The Rankine cycle efficiency depends on: the working fluid, boiler (evaporator), expander, condenser and working fluids operating parameters (mass flow rate and pressure).

On the basis of these results, our future work will be focused on numerical and experimental study of the impact of waste heat recovery system Rankine cycle-based on the performance of the internal combustion engine.

Acknowledgments

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