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Bottoming cycles for electric energy generation: Parametric investigation of available and innovative solutions for the exploitation of low and medium temperature heat sources

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ABSTRACT

Many industrial processes and conventional fossil fuel energy production systems used in small-medium industries, such as internal combustion engines and gas turbines, provide low or medium temperature (i.e., 200–500 °C) heat fluxes as a by-product, which are typically wasted in the environment. The possibility of exploiting this wasted heat, converting it into electric energy by means of different energy systems, is investigated in this article, by extending the usual range of operation of existing technologies or introducing novel concepts. In particular, among the small size bottoming cycle technologies, the identified solutions which could allow to improve the energy saving performance of an existing plant by generating a certain amount of electric energy are: the Organic Rankine Cycle, the Stirling engine and the Inverted Brayton Cycle; this last is an original thermodynamic concept included in the performed comparative analysis.

Moreover, this paper provides a parametric investigation of the thermodynamic performance of the different systems; in particular, for the Inverted Brayton Cycle, the effects of the heat source characteristics and of the cycle design parameters on the achievable efficiency and specific power are shown. Furthermore, a comparison with other existing energy recovery solutions is performed, in order to assess the market potential. The analysis shows that the highest electric efficiency values, more than 20% with reference to the input heat content, are obtained with the Organic Rankine Cycle, while not negligible values of efficiency (up to 10%) are achievable with the Inverted Brayton Cycle, if the available temperature is higher than 400 °C.

1. Introduction

In several applications of many industrial sectors the seek for low-cost electric energy generation and the demand for increasing values of the fuel conversion efficiency are emerging requirements, while in most of the cases the heat demanded by process is not a problem as it can be easily covered with high thermal efficiency boilers. Moreover, in some cases low or medium temperature exhaust heat fluxes may be present in the industrial plant, when fossil/renewable fuel engines or gas turbines are used or when the boilers output heat is not fully exploited. For example, an internal combustion engine can provide exhaust gases at temperature values typically of 300–450 °C, a gas turbine is characterized by exhaust temperature of 400–550 °C and micro gas turbines can give 250–350 °C; other industrial heat fluxes, e.g. exhaust from ceramic desiccant ovens, concrete kiln gas, leather or food industry discharge heat, can provide similar temperature values ranging from 200 °C to 500 °C, depending on the process operation.

The available low or medium temperature heat could be profitably exploited by means of a thermodynamic cycle, conceived as bottomer of the heat production process. Typically, in many small-medium size industrial applications, the amount of thermal power discharged by the topping process can be of the order of magnitude of some hundreds of kW, values not compatible with the adoption of superheated water–steam turbine cycles, with complex and multi-level regenerated architecture, typical of large size power plants and granting high efficiency values.

1.1. Brief overview of available technologies for small size heat recovery

Different small size heat recovery systems could be used to exploit the available limited size heat sources, namely Organic Rankine Cycles (ORC) [1] and Micro Rankine Cycles (MRC), Stirling engines [2,3] and also Thermo-Electric (TE) systems [4]; some of these technologies are not yet fully developed (mainly MRC), while

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Nomenclature

Acronyms

C	compressor
CHP	Combined Heat and Power
IBC	Inverted Brayton Cycle
IC	inter-cooler
LHV	Lower Heating Value
MRC	Micro Rankine Cycle
ORC	Organic Rankine Cycle
REC	recuperator
T	turbine
TE	Thermo-Electric
TI	thermionic
TPV	Thermo Photo Voltaic
Stir	Stirling cycle

Symbols

p_{low}	IBC minimum pressure (bar)
Q_{used}	specific heat at bottoming cycle inlet (kJ/kg)
Q_{avail}	heat available from the source (kJ/kg)
R	gas constant (kJ/kg K)
s	specific entropy (kJ/kg K)
T	temperature (°C)
T_{out}	hot gas outlet temperature (°C)
T_{max}	hot source temperature (°C)
T_{min}	cold source temperature (°C)
T_{vap}	ORC vaporization temperature (°C)
V_{max}	Stirling internal maximum volume (m^3)
V_{min}	Stirling internal minimum volume (m^3)
$X_{H2O\ in}$	water mass fraction at IBC inlet (–)
$X_{H_2O\,k}$	condensed water mass fraction (–)
$Y_{H_2O\,Sat}$	air saturation water volume fraction (–)
W	specific work (kJ/kg)
W_{Stir_id}	Stirling ideal cycle specific work (kJ/kg)

Greeks

ε	heat recovery effectiveness (–)
η	bottoming cycle efficiency (–)
η_{el}	electric auxiliaries efficiency (–)
η_{gas}	real gas efficiency (–)
η_i	indicator diagram efficiency (–)
η_o	organic efficiency (–)
η_p	polytropic efficiency (–)
η_{rec}	total heat recovery efficiency (–)
η_{rrc}	reversible recuperation cycle efficiency (–)
η_{Stir_id}	Stirling ideal cycle efficiency (–)
η_{II}	irreversibility recuperation cycle efficiency (–)

other are commercially available (ORC, Stirling, TE) but a limited number of producers and of machines could be found (see Table 1 reporting a summary of representative producers and size units for the different considered technologies).

Both the ORC and MRC systems perform a closed thermodynamic cycle similar to the reference Rankine, based on the sequence of: (i) evaporation, exploiting the heat provided by the hot source; (ii) expansion, producing output power; (iii) condensation, discharging unused residual heat; and (iv) fluid pressure augmentation, with pump.

Moreover, the ORC are typically recuperated cycles, to increase the heat recovery and the efficiency (Fig. 1a shows a recuperated ORC layout); refrigerant fluids, hydrocarbon or other particular fluids (siloxanes, i.e. high molecular weight polymerized organic compounds including also silicon and oxygen) are used in the ORC, allowing for dry expansion [5], thus avoiding the problems of turbine operation with a two-phase flow (see a simplified *T–s* diagram in Fig. 1b, for a dry fluid).

The MRCs, currently under development for output sizes of few kW and oriented to domestic applications, are typically not recuperated, some models are water based (e.g., Otag, Cogen Microsystems), with very simple volumetric expanders and the input heat is provided by a flame, producing a hot gas stream (in most cases inlet temperature can be estimated in the range of 700–800 °C) facing directly the evaporator component, where the steam evaporation temperature is lower than the hot source temperature and can vary in a wide range, depending on the system design.

The Stirling machine (which can adopt different complicated kinematics structures, [2,3]) is basically an external combustion engine, with an internal fluid (air, helium or other) performing a thermodynamic cycle with values of efficiency which should ideally reach the reference Carnot cycle value; nevertheless, due to the complex architecture of the engine and the strong irreversible processes occurring during the system operation, the actual values of efficiency granted by the existing machines are always lower than 30%; moreover, the current realizations of Stirling engines are operated with an external combustion system, providing the input heat at relatively high temperature (typically 650–800 °C).

The TE systems, based on the semiconductor technology, accomplish the direct conversion of heat into electric power without thermodynamic transformations and without moving parts (the TE exploits the Seebeck–Peltier effect, occurring also under limited temperature differences, down to less than 100 °C, and with hot side temperature ranging between 200 and 400 °C, values compatible with the temperature range in study). Due to its operating principle, the TE system cannot be considered as a bottoming thermodynamic cycle; nevertheless, TE is a possible low temperature heat recovery technology and thus it is included in the present study only for comparison purpose.

Table 1
Small size heat recovery technology producers.

Technology	Producer	Electric power size (kW)	Technology	Producer	Electric power size (kW)
ORC	Turboden (ITA)	200–2000	Stirling	Bioenergy STM (USA)	38, 43
	Infinity turbine (USA)	30–500		WhisperTech Ltd. (NZ)	1
	UTC power (USA)	280		Solo Stirling GmbH (CH)	2–9
	Ormat (USA)	250–2000		Stirling Denmark (DK)	33
	Ingeco (ITA)	100		Microgen (USA)	1
MRC	Energetix group (UK)	2.5		Infinia Corp (USA)	1
	Otag (GER)	2.1		Disenco (GER)	3
	Ormat (USA)	0.2–4.5	TE	Hi-Z technology Inc (USA)	2×10^{-3}–2×10^{-2}
	Cogen microsystems (AUS)	2.5, 10		Global termoelectric (USA)	0.02–0.55
				Kryotherm (RUS)	10^{-3}–10^{-2}