Advanced Waste Heat Recovery Systems with Energy Storage for Optimum Performance, Availability and Sustainability in Ships: A Review

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Abstract: This article presents review of the design and performance features of the emerging WHR technologies of interest to marine platforms viz., compact supercritical-transcritical CO_2 based power and/or cooling system; thermoelectric generators and thermal energy storage (TES) systems to enhance combat effectiveness of future platforms. It is seen that such modular systems integrated with TES systems would not only result in additional power density and energy efficiency but also result in low maintenance, reduced operating cost, and enhanced operational availability of future platforms. Further, the proposed systems will also result in additional endurance/ range and significant reduction in annual carbon footprints.

Keywords: Waste heat recovery (WHR); Supercritical-Transcritical Carbon dioxide; Thermo-electric generation (TEG) system; Thermal energy storage (TES) system; Operational availability.

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1. Introduction

The growing need of energy has emphasized the need for energy efficient and cost effective methods of power generation. While IC engines are the stalwarts in generating maximum amount of energy for mankind, they continue to be a largely inefficient source rejecting nearly 50% of energy to atmosphere with largest part being exhaust gases, nearly 30-40% while remaining through coolant and radiation [1]-[3]. Further, drivers such as depleting fossil-fuel reserves and hence, rising fuel costs together with rapidly expanding fleet size and the increasing deployments have resulted in a sharp rise in the fleet's operating cost. In addition, emerging global concerns about climate change have resulted in stringent regulations requiring maritime sector to implement measures for reduction of greenhouse gases (GHGs), NO_X, SO_X and particulate matter (PM) emissions from the shipping. Recently, IMO has mandated strict regulations for ships to implement mechanisms such as energy efficiency index called as "Energy efficiency design index or EEDI", "Energy efficiency operational index or EEOI", and "Ship energy efficiency management plan or SEEMP", applicable for all marine vessels of 400 gross tonnage or above, engaged in International waters as per IMO (2016). Among the various measures available, the most sustainable and effective option having a significant potential of improving ship's energy efficiency is integrating an energy efficient waste heat recovery (WHR) or bottoming cycle to shipboard power plants through the combined cycles. Integration of conventional gas turbine power plant (rated above 10 MW) with a suitable bottoming (WHR) cycle can significantly decrease the mean temperature of heat rejection, and thus improve its overall energy efficiency and realise significant fuel savings of the order of 5-15%, depending upon the waste heat source [6]. Recently, the supercritical carbon dioxide (sc-CO_2) power cycles and thermoelectric power systems have emerged as the most promising energy conversion cycles, particularly for the applications where the compactness, light weight, high efficiency and power density form the essential part of the design criteria.

2. Supercritical CO_2 Brayton Cycle based Power Plants

The supercritical CO_2 cycles originally referred to as 'Feher cycles', principally use carbon dioxide (R744) as the working fluid entirely in its supercritical phase i.e. region above the critical point. Carbon Dioxide (CO_2) has a critical point at 30.98 ^{0}C or 304.3 K and 73.8 bar. Recently, it has caught the attention of researchers across the world due to the unique thermo-physical properties exhibited by it in its supercritical state, such as lower critical point temperature and moderate critical point pressure, higher density during supercritical state, lowest-GWP and nil-ODP, compared to conventional working fluids. Besides low critical point, CO_2 has high critical density compared to conventional fluids such as steam. These feature enables the supercritical CO_2 (SC-CO_2) to be associated with unique advantages such as completely avoid the phase-change (vaporisation) process, reduced compression work as working fluid behaves more like a liquid than a gas, leads to better expansion work output and lesser number of turbine stages. All of these features are conducive for its use as an effective and sustainable working fluid in power generation applications. The supercritical CO_2 Brayton cycles have been reported to be extremely compact, light and superior in performance than the conventional power cycles based on several studies in past for a large number of applications like next generation nuclear reactors, concentrated solar power (CSP), automotive, geothermal power and fuel cells etc. [4]-[5] presented the energy and exergy analysis of an advanced waste heat recovery system using supercritical CO_2 as the working fluid in regenerative Brayton cycle for WHR in a shipboard application. **Fig. 1** shows the schematic diagram of the supercritical CO_2 regenerative Brayton cycle (RBC) based waste heat recovery system for shipboard application.

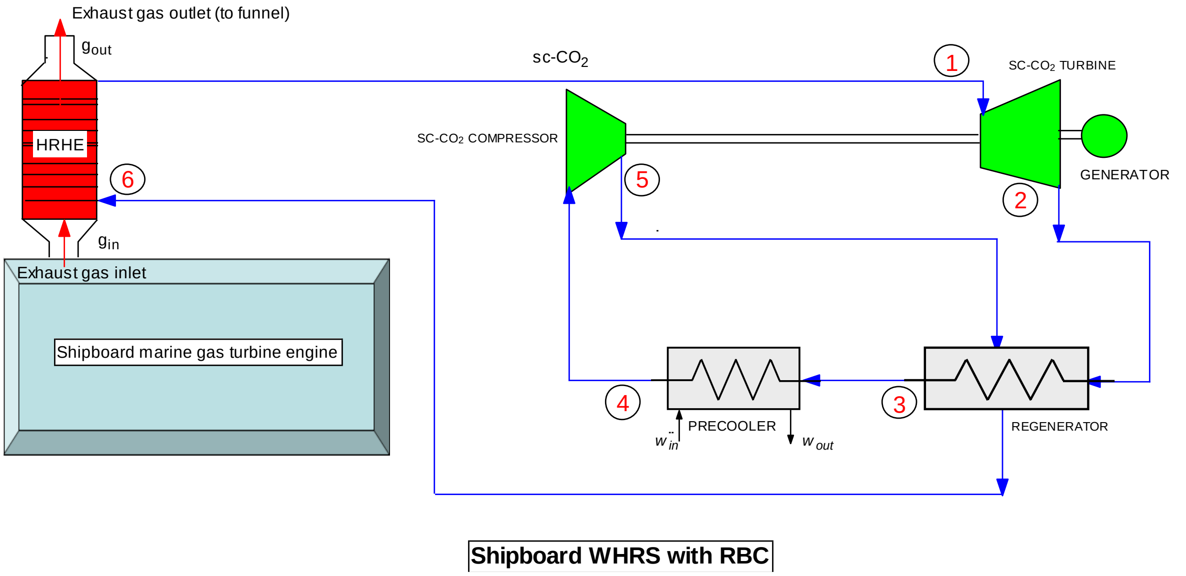


Fig. 1. Schematic of the SC-CO_2 RBC for shipboard WHR and power application

The performance features of SC-CO_2 RBC based WHR simulated for a marine gas turbine (LM2500) in a typical shipboard platform is presented in Table 1 below. The economic & environment performance parameters shown include estimated installed cost, annual fuel savings (in US$ and INR equivalent), simple payback period (without incentives, in year and months), carbon emissions saved (tons/yr) and carbon credits accrued (INR/yr). It is seen that, with the proposed WHR system, significant amount of carbon credits can be earned annually, that may vary from about INR 71 Lakhs at the 100% relative GT load (design point) to about INR 50 Lakhs at 60% relative GT load. Further, it is also seen that the carbon emission savings varies from around 7275 (ton-[CO_2]/yr) at 100% relative GT load (design point) to around 5125 (ton-[CO_2]/yr) at 60% relative GT load [4].

Table 1 Performance features of SC-CO$_2$ RBC based WHR system simulated for a marine gas turbine (LM2500) in a typical shipboard platform

Relative GT Load / Performance Parameter	**(%)**	**100 (*)**	**87**	**73**	**60**
$\eta_{I,RBC}$	(%)	31.6	30.9	30.3	29.5
$\eta_{I,TC}$	(%)	33.6	32.5	31.1	29.5
$\eta_{II,TC}$	(%)	45.8	44.2	42.3	40.1
$\eta_{I,CC}$	(%)	41.9	40.7	39.4	37.9
$\eta_{II,CC}$	(%)	56.9	55.4	53.6	51.6
Net Power Output	(kW)	4108	3707	3300	2894
Fuel Savings	(Million USD/yr)	8.908	8.039	7.157	6.275
Fuel Savings	(INR Cr /yr)	57.9	52.3	46.5	40.8
Simple Payback Period (without incentives)	Year	2.47	2.74	3.07	3.51
Simple Payback Period (without incentives)	Months	30	33	37	42
Carbon Emissions Saved	(ton-[CO$_2$]/yr)	7275	6565	5845	5125
Carbon Credits Earned	(USD/yr)	1,09,129	98,480	87,681	76,876
Carbon Credits Earned	(INR/yr)	70,93,385	64,01,200	56,99,265	49,96,940

*Design point is assumed as the relative GT load, corresponding to 80% shipboard GT rated load (= 16.8 MW)

The investment cost of the plant per kW taken as 2200[$/kW] [Persichilli et al.(2012)]; RBC: Bottoming cycle; TC: Topping Cycle (shipboard LM2500 GT); CC: Combined cycle: TC + RBC.

3. Transcritical CO_2 Vapor Compression Cooling Cycle (RVCC) based Green Air-Conditioning and Refrigeration Plants

Extensive R&D efforts are being directed worldwide towards developing new, environmental-friendly and natural refrigerants as alternatives to conventional harmful refrigerants. The recent research on CO_2, and due to its distinct advantages, R-744 is fast emerging as a credible natural substitute for the harmful refrigerants in compact refrigeration & air-conditioning systems. For example, R-744 is safe (non-flammable, non-toxic), has nil ozone depletion potential (ODP=0), has lowest global warming potential (GWP=1), stable, inexpensive and found abundantly in nature. In addition, it possesses favourable thermos-physical properties such as high density, specific heat, high volumetric refrigeration capacity, latent heat and thermal conductivity besides having nil recycling issues [5].

The RVCC based air-conditioning and refrigeration plants utilise closed-loop refrigeration cycle operating on CO_2 (R-744) as the refrigerant. RVCC is a regenerative vapor compression cycle that runs in a closed-loop cycle where the compression process occurs in the gaseous phase (like RBC) whereas the throttling and the evaporation processes occur in the subcritical (liquid & gaseous) phase. Also, the low pressure (or the evaporating pressure) of the cooling cycle is ensured below the critical point. Since the cycle operates partly in the supercritical region (compressor outlet, gas cooler and hot stream of the forecooler) and partly in the sub-critical region (expansion valve or throttling valve, evaporator and cold stream of the forecooler), this type of CO_2 refrigeration cycle is referred to as Transcritical-CO_2 regenerative vapor compression cooling cycle or RVCC. It consists of basically five main components, compressors, heat exchangers viz., forecooler, evaporators, gascooler or precooler, an expansion valve or throttling valve or an ejector and an internal regenerator or forecooler for internal heat recovery. **Fig. 2** shows the schematic layout of a simple RVCC.

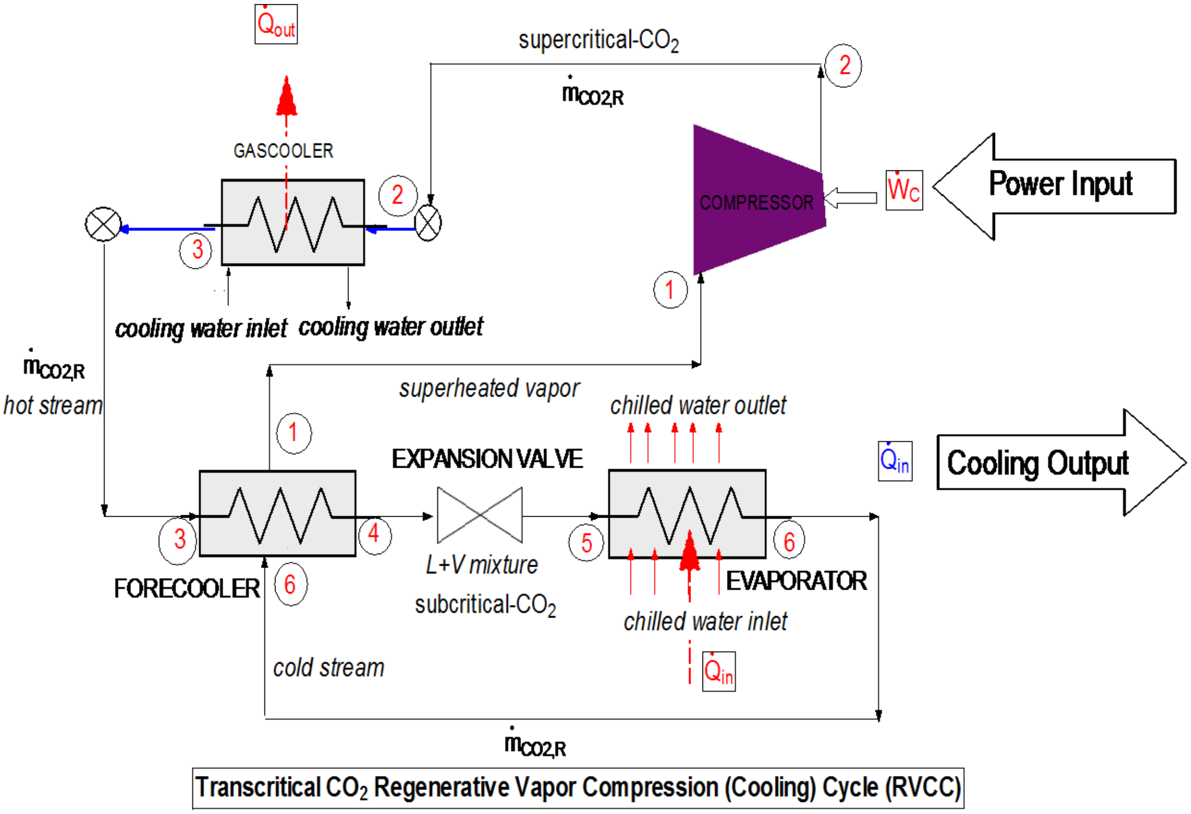


Fig. 2 Schematic layout of simple RVCC for shipboard cooling application

4. Supercritical/ Transcritical CO_2 Combined Power and Cooling Systems

In another approach, the supercritical CO_2 Brayton power cycle (RBC) and transcritical vapor compression cycle (RVCC) can be thermodynamically coupled to provide both WHR based power and cooling thereby accruing the advantage of greater flexibility, low maintenance and higher operational availability for shipboard platforms. **Fig. 3** shows a schematic layout of such a novel RBC-RVCC combined power and cooling cycle for a typical shipboard platform.

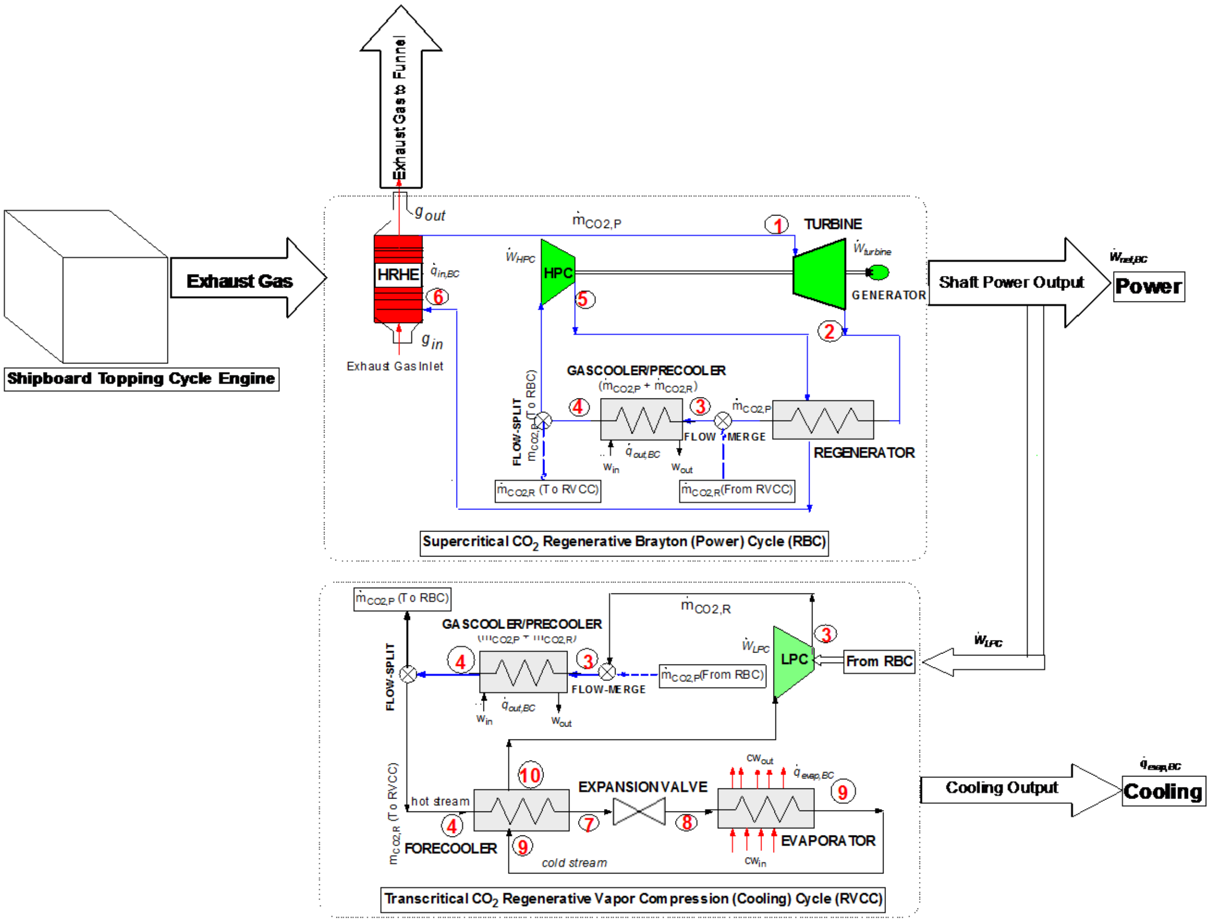
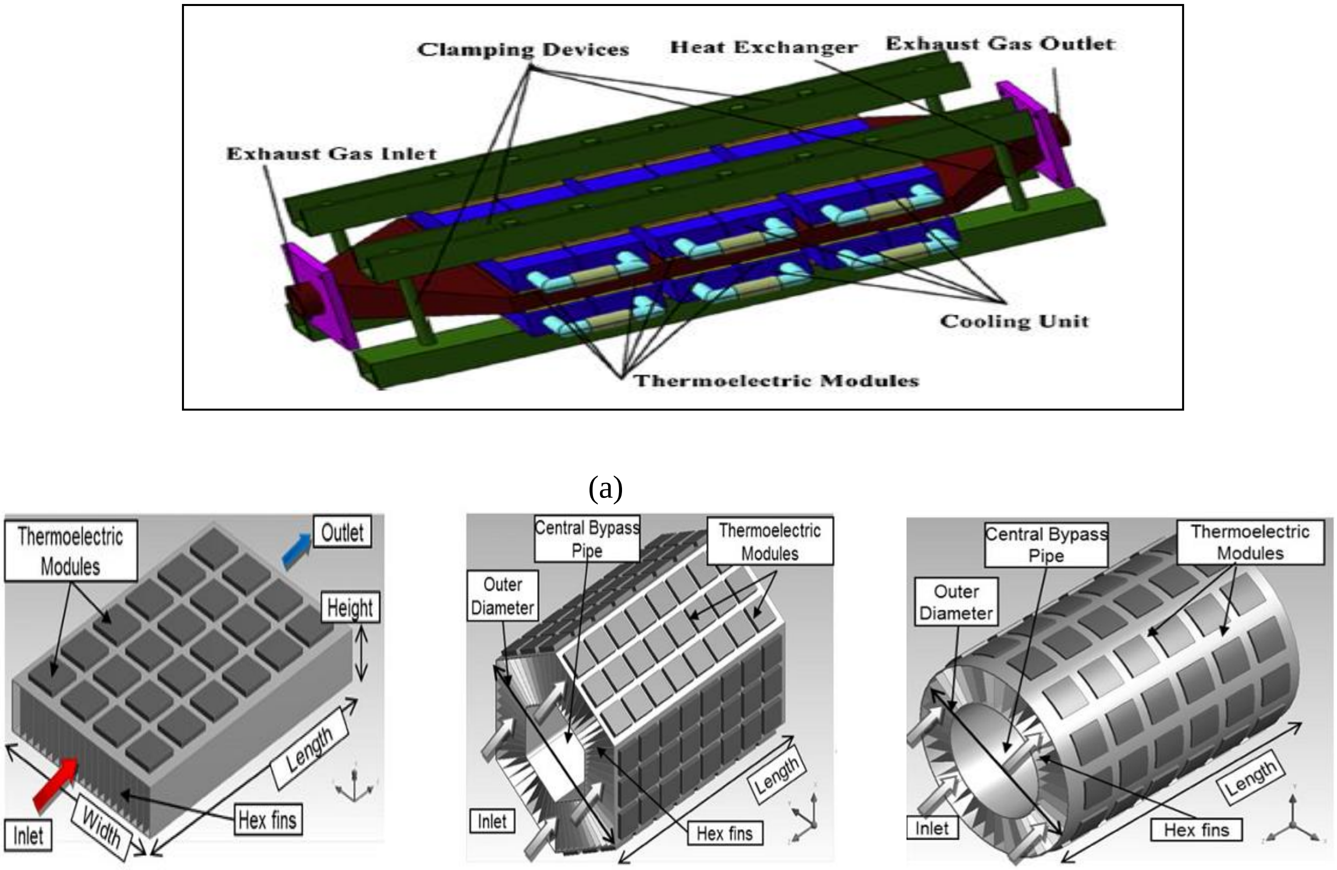


Fig.3. Schematic layout of novel supercritical/transcritical CO_2 RBC-RVCC based combined power and cooling cycle for shipboard platform

The proposed RBC-RVCC combined system is expected to be a low maintenance technology due to maintenance-free compressors and reduced size and number of cycle components as compared to conventional systems. Further, such systems will be more energy efficient and will increase operational availability. The salient advantages of RBC power system integrated with RVCC cooling system for shipboard applications are augmentation of shipboard power and cooling capability by about 18% and 15% of the shipboard GT's rated power respectively at its full load. Also, the overall energy efficiency of the shipboard power plant is expected to improve by almost 30% [5].

5. Thermoelectric Power Systems

Similar to above WHR based compact power and cooling systems, the thermoelectric power generation is yet another effective step in the direction of enhancing energy conservation and green technology to improve operational effectiveness and sustainability in a marine platform. Here, the exhaust of shipboard diesel engines is used as low temperature direct heat source for generation of electricity using thermoelectric power generators. Thermoelectric power generators are the solid-state devices which convert thermal gradient directly to electric potential by Seebeck effect [7]. The Thermoelectric power generation technology offers distinct advantages, such as: (a) TE conversion is reliable and operates in silence compared with other energy conversion technologies, as it works without mechanical movement; (b) TE devices are simple, compact, safe, highly scalable; and (c) it is an environmental friendly green technology [8]. Therefore, directly converting the waste heat into electricity by thermoelectric device is considered as an attractive solution provided that the conversion efficiency (ZT) is high enough to overtake the traditional WHR technologies currently in use. A schematic of a typical ETEG is shown in **Fig 4(a)**. The efficiency of ETEG is largely dependent on four factors (a) Hot side/cold side heat exchanger geometry; (b) Heat exchanger material; (c) Site of installation of ETEG and (d) Cold side temperatures[9]. The three salient configurations of hot side heat exchanger geometry are: rectangular, hexagonal/octagonal, cylindrical as shown in **Figs 4 (a) (b), (c)** and **(d)** respectively.



(a)

(b) (c) (d)

Fig 4. Three basic geometries of ETEG (a) Typical TEG model (b) Rectangular geometry (c) Hexagonal geometry (d) Cylindrical geometry

As regards to shipboard applications of TEG power systems, [10] simulated the potential of TEG power on a medium size bulk carrier and found that there exist a potential of generation of 42.4 kW electrical power from main propulsion engine exhaust after boiler. However, the performance can be enhanced by installing the TEG closer to engine and using more efficient TE modules reviewed all possible means of WHR and brought out huge potential of thermoelectric system as a clean system on marine platforms. While TEG systems installed on automobiles have been reported to suffer a significant loss due to the losses caused in pumping the cooling medium for extracting heat from TE modules, similar issues are not encountered in a marine platform due to liberal supply of sea water as cooling medium. Considering the potential of TEG technology onboard marine platform, the cylindrical TEG can be viewed as a possible replacement of exhaust gas coolers onboard future marine platforms.

6. Thermal Energy Storage (TES) Systems

‘Thermal Energy Storage (TES)’ is a well-known concept which has been tested and proved over time for efficiently storing energy when demand is relatively less and utilising when demand is relatively more. TES systems can be mechanical, chemical or electrical in nature, based upon the applications energy can be changed to different forms. TES can be used mainly in systems requiring sudden boost of energy or simply to balance the mismatch in demand and supply, especially for heating/ cooling applications, TES have ability to offset the difference both in time and magnitude for heat / cooling requirements. This ability of TES can be exploited in marine applications for WHR systems. Although TES involves some losses during charge and discharge cycles, impacting the efficiency of the system, it also enables variable electricity production to provide time-shifting and peak shaving, balancing of ancillary services and avoids renewable curtailment.

Based on the energy storage and dissipation, the thermal energy storage systems can be broadly classified as latent heat, sensible heat and chemical heat as shown in **Fig. 5**.

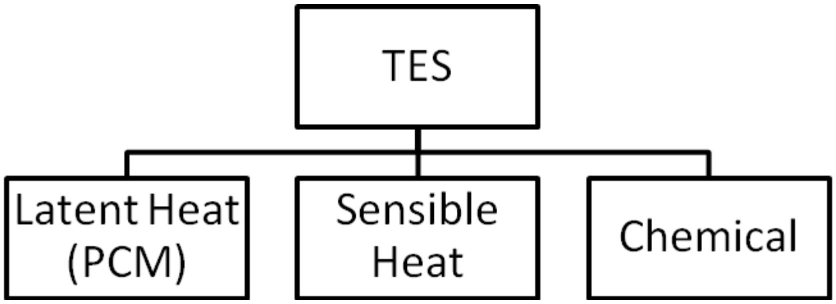


Fig.5 Types of Thermal Energy Storage (TES) Processes

(a) Sensible Heat based TES

Through the sensible heat based TES, thermal energy storage at temperature range of -40^{0}C to +400^{0}C is possible. Each storage method imposes its own advantages and disadvantages. If energy storage is in the form of sensible heat, specific heat of the material defies the thermal storage capacity and also enclosure play an important role in term of thermal losses. Presently, water is used as a medium for TES for large industrial applications, but has limitations in terms of specific heat and transfer rates. The entire systems are mainly dependent on the hydrogeological conditions. Moreover, these systems cannot be used for shipboard applications considering the space limitations and the dynamic requirements for energy transfer rates.

(b) Latent Heat/ Phase- Change-Material (PCM) based Thermal Energy Storage (TES) Systems

To overcome the disadvantages of systems using sensible heat, the latent heat also referred to as the Phase change materials (PCM) based systems offer a higher storage capacity in terms of latent heat for the phase change. PCMs in addition facilitate a target-oriented temperature discharge associated to specific heat for phase change. Further use of PCM has limitations for use in application of humidity control and timely maintenance. PCM have shown a promising future for applications with space constraints requiring higher specific heat. PCM uses latent heat for changing phase of the material and invariably storing energy[11]. The most common change of phase applied is the change from solid to liquid, but using the change of phase from liquid to gas is presently experimented for and has indicated favorable results. Present day PCM technology can be used for a temperature range of -10^{0}C to +150^{0}C. PCM can be considered as replacement for hot water cylinders in future or as a complementary resource. PCM systems have a limitation for time shifting electricity use or for increasing self-consumption of self-generated PV electricity. PCM applications for cooling are more advanced than the heat storage.

PCM based TES systems can be utilised for future shipboard applications especially in the field of heat exchangers. But the main disadvantage of such systems is relatively high costs and their performance is sensitive to the temperature at which material changes phase. Hence, PCM based systems are viable only for temperature range for desired application based on temperature at which material changes phase. Whereas for a wider temperature range of operation sensible heat storage approaches provide a stronger alternative.

(c) Thermo-chemical storage (TCS) based TES Systems

To overcome the humidity control Thermo-chemical storage (TCS) which are primarily of Thermo-chemical reactions which offer even higher storage capacities can be used. TCS accumulates thermal energy in the form of heat/ cold and can be utilised based upon the demand, further it enables control on humidity[12]. Presently, TES systems based on sensible heat have been commercially proved out concept and available readily, while TCS and PCM-based storage systems under research phase, few of these systems have been specifically built for an application and successfully tested.

(d) Thermochemical Heat Storage (THS) based TES Systems

Thermochemical Heat Storage (THS) has low energy density, high volume of stores and high temperature storage, and hence the potential to overcome some of the inherent challenges faced by other TES technologies, However, THS is currently being experimented upon, with the bulk of the activity firmly embedded in basic research mainly in academia. THS use the principle for separation of two substances; substances are either two liquids or a solid and a vapour. The substances are bound by number of physical principles or binding forces[13]. The storage of heat is achieved through the separation of these substances. The capacity of storage is directly propositional to the force binding the materials resulting in higher temperature required to separate the two materials and therefore to store the heat. Energy density changes with increase in temperature and is in the range of 30^0C: for physical sorption caused by surface forces, above 1000C for chemical sorption caused by covalent attraction and above 200^0C for Chemical reactions caused by ionic forces. THS provides much higher storage capacities per mass or volume compared to sensible or latent heat storage, the role it could play is substantial. But based on the current state in research it is unlikely that THS applications will be commercialised within the next 10 years.

7. **TES System Variants for Shipboard Applications**. A comparison of the various variants of TES systems is summarised at **Table 2**. It is evident from **Table 2** that TES application have been currently utilised for certain building/ construction industry requirements and is found to have a great potential in curbing Carbon emissions. Despite their distinct advantages, TES systems have not been commercialised since due to higher footprints, weight and higher cost per unit volume of energy storage in comparison to conventional energy storage devices such as. Latent heat based TES utilising phase change materials (PCM) are presently used for shipboard applications, but are limited to hot water applications and very recently for Heating, Ventilation and Air-Conditioning (HVAC) applications of very limited size. Due to its advantages of higher energy storage capacity and compactness, THS technology is seen to have a great potential and same is widely being researched upon throughout the world for future land based as well as shipboard applications.

Table.2 Comparison of various TES System Variants

Ser.	Variant	Types	Advantages	Disadvantages	Possible Applications
1	Latent Heat	TTES, PTES. BTES,A TES	Reduce Carbon Emissions	Hydro geological Dependent	AC System, Heaters (Building / Construction)
2	Latent Heat (PCM)	Glycol, Wax, Inorganic Compounds	Higher energy density per volume	Limited temperature zone	Hot water Systems
3	TCS	Lithium, Hydrogen	Humidity control	Volatile in Nature	Battery. Fuel Cell
4	THS	Carbon	High storage capacity	Nascent technology	sc-CO_2 Systems

Conclusion

8. Increasingly diversified operating profiles of new combat platforms and resultant fluctuating power demands, warrant need for WHR systems and an energy storage technology integrated with power generation and management system. The emerging WHR and TES systems presented above can address such needs. Additionally, due to optimal loading of all primemovers, overall power plants will be optimised and will lead to lower maintenance issues and better operational availability eventually leading to enhanced combat effectiveness of future marine platforms.

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