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Review Article

Low-grade (waste) Energy Conversion: Science and Technological Challenges

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Waste heat, in a classical definition, means the heat emitted by any process or utility, which cannot be economically harnessed or recycled within the process. With increasing costs of energy, the waste streams will require sliding down temperature scales for meeting the new economic viability. This means what was "good" for waste streams coming out of the process at 130°C yesterday will be imposed a penalty today and it may be demanded that the temperature has to be lowered to less than 80°C.

This paper describes how to "bridge" this new paradigm in an existing system using modern tools so that the system becomes efficient and hence sustainable. In the current discussions on energy security, energy efficiency and reduction in CO_2 to manage climate-change, waste heat energy conversion is an excellent mitigation tool. Today, modern tools such as process pinch technology, resource optimization modeling and new energy conversion devices for waste heat into useful energy, make it possible to examine every industrial process with these tools and integrate it with energy conservation measures. The paper describes all the aspects about the waste heat generated in different industrial segments, the pinch technology and resource optimization tools as well as various waste to energy options. Prominent among the energy conversion devices, Organic Rankine Cycle (ORC), which can convert even low-grade energy into electricity, is discussed in detail.

Adoption of these 'Waste To Energy' (WTE) technologies will have an enormous positive impact and saving of precious primary resources such as oil & gas and hence form a very critical component in the debate on energy security. Also, waste heat to energy means saving in CO_2 emissions, an important tool, which can mitigate the global warming.

Keywords: Organic Rankine Cycle (ORC); Heat Pump; Chiller; Pinch Technology; Climate Change

Background

Industrial processes use energy for conversion of raw materials into finished product(s). In this process of conversion, various transformations of energy and mass take place within the process and, at the end of the process, the products and effluents emerge from the process. Effluents contain constituents which are declared as "waste" both in their form (mass) and heat content. Efficiency (η) of any process is therefore defined as ratio of output (desired) to input and (1-η) times the input is a measure of the waste generated from the process.

Thermodynamically, therefore, any process of conversion results in increased entropy which in turn ends up in the undesired product and energy being disposed into the "sink." The increase in entropy of the universe is precisely due to this. While the first law of thermodynamics always conserves the energy and mass, the second law of thermodynamics correlates the quality of energy utilized and brings in

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the concepts of exergy and Carnot efficiency. Most of the waste energy from the process is closer to the sink or the ambient conditions and hence poses a challenge in harnessing the same. The singular challenge in waste energy is that it is a large quantity but with quality closer to sink levels. Thus, a 500 MWe power plant generates nearly 800 MWe of waste heat close to 48°C closer to the sink conditions.

Early in the industrial development phase (nineteenth and most part of twentieth century), the focus was clearly in terms of obtaining the desired product in large quantities with very limited attention to the efficiency aspects. This resulted in almost every synthesis and industrial process utilizing enormous quantities of energy and raw materials making waste inevitable, set off from any industrial activity. Even the electricity generating technology based on Rankine cycle is built on a 30% conversion efficiency resulting in loss of two-thirds of primary energy (coal or oil & gas) as waste energy.

Energy Efficiency as the Key

Only in the early seventies and late eighties, when the world woke up to the reality of the exhaustible nature of energy resources and the toxic impact of effluents from industrial activities on nature including the climate change challenge posed by the use of fossil fuels, the need for examining the processes from the efficiency lens began. Enhancing the efficiency of the process by process intensification, energy efficiency and use of low grade energy became the key feature of the industrial process development. The impact of such development is immediately evident from the fact that today automobiles consume one-fifth of the diesel consumed three decades ago, ammonia fertilizer plant consumes less than half the energy consumed by plants designed in the seventies, power plants produce power at 50% more efficiency than the early generation power plants and the list goes on.

The thrust therefore has been three-fold, viz., (1) at a very basic level, explore options of energy recovery within the process itself (pinch technology and resource optimization), (2) carefully evaluate the balance energy exiting as waste energy and (3) build appropriate technologies for utilization of the waste heat within the process itself or integrate it within the utility systems. This three-tier system would be the underpinning of the waste to energy conversion strategy for the industry.

Each of these steps is discussed in subsequent paragraphs of this article. Before we do that, Table 1 and Fig. 1 provide a glimpse on the waste heat from various Indian industries and the total potential of recovery of such energy. Apportioned energy reduction in the selected main industrial sectors is to the tune of 3.53 MTOE (Million Tons of Oil Equivalent) (Kumar, 2012), which forms a substantial portion of the energy generated in India. Fig. 1 depicts the bar graph of industry-wise waste energy potential in equivalent TOE (Tons of Oil Equivalent).

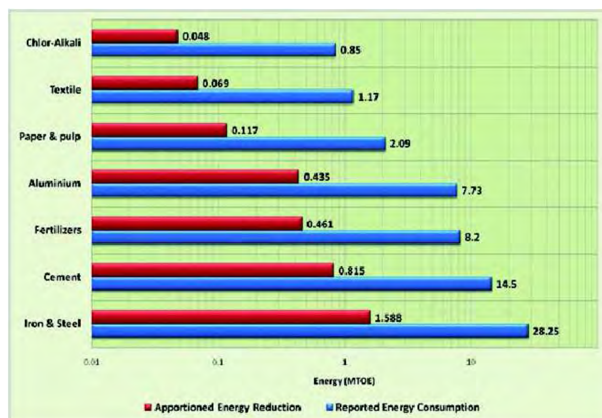

Fig. 1: Indian industry – energy scenario (Kumar, 2012)

Pinch – Resource Optimization – Waste to Energy Technologies

Pinch technology (Shenoy, 1995) is a powerful tool to identify energy recovery within the process itself so that the net energy requirements can be minimized to a large extent. In this approach, any complex process is systematically decomposed into various streams where the hot fluid needs to be cooled and cold fluid needs to be heated. A coupling is established using a GCC (Grand Composition Curve), which identifies the temperature beyond which heat is to be added and the temperature below which heat is to be removed from the process.

Table 1: Indian Industry – Energy scenario (Kumar, 2012)

S.No.	Industry	No. of identified consumers	Reported energy consumption (MTOE)	Shared percentage (%)	Apportioned energy reduction (MTOE)
1.	Iron and steel	74	28.25	44.99%	1.588
2.	Cement	84	14.5	23.09%	0.815
3.	Fertilizer	29	8.2	13.06%	0.461
4.	Aluminium	10	7.73	12.31%	0.435
5.	Paper and pulp	31	2.09	3.33%	0.117
6.	Textile	90	1.17	1.86%	0.069
7.	Chlor-alkali	22	0.85	1.35%	0.048
	Total	**340**	**62.79**	**100%**	**3.533**

Fig. 2 depicts these concepts of pinch technology in a typical process of distillation where multiple energy exchange takes place with some streams needing heating and some streams cooling. The first law of thermodynamics shows that net heat needed is only 80 kW and the pinch analysis shows that the pinch temperature is 115^{o}C; and further analysis depicts the way the heat exchange must be organized which is not so obvious if carried out in a conventional manner.

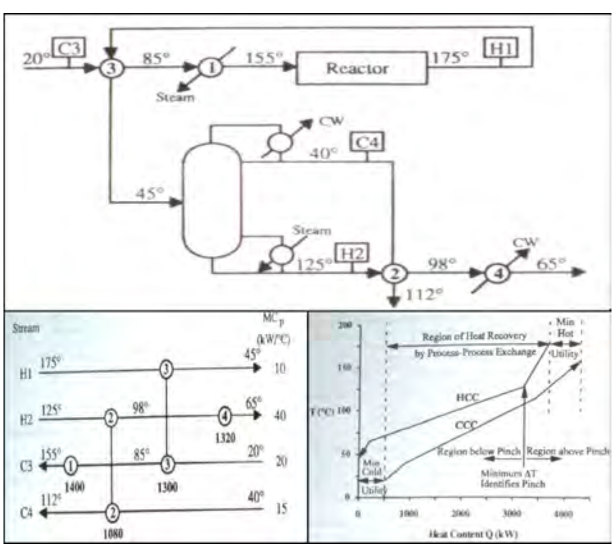

Fig. 2: Concepts of pinch technology in distillation process

The hot utility for the illustrated process is 605 kW at temperatures above 120^{o}C and cold utility is 525 kW at temperatures below 18^{o}C. This analysis can save the energy needs of the process by a very large percentage to the tune of 50% to 250%. The need for larger heat transfer area and heat exchanger network is the only limiting factor in aiming for higher extraction of energy. The approach used in the heat exchanger determines the minimum approach temperature for the pinch analysis.

Once these limits are established, then the problem moves to the second stage of the resource optimization domain to organize the most optimum way for the utilities to be managed. Here, the energy needs of the process for heating, cooling and electricity generation can be met with a poly-generation facility which combines the heat and power in the most elegant manner to maximize the efficiency of the combined system.

After this phase of analysis, the process presents itself for carrying out the "waste heat" review and technologies needed for recovering this balance energy in the most effective manner. The generation of waste energy is directly proportional to the fine tuning of the first two processes, viz., if the first two processes are carried out in a coarser manner or the process constraints pose limitation to extract energy from within the process, then, the net energy escaped from the process – which is waste energy– will need to be managed using the waste heat technologies.

Waste to Energy Options

The waste to energy (WTE) technologies can be grouped under the following two concepts. The first is the heat pumping technology, where the waste energy available can be converted into cooling energy or some intermediate level of energy or even transform the lower energy into higher grade energy. These are carried out using the concept of heat pumping – a unique methodology using a two-component mixture cycle. The two-component two-phase systems can be coupled in different ways to convert the low-grade energy into cooling energy (below ambient), or higher grade energy (higher than the waste grade) or even a lower than lower grade energy (hot water) depending on the applications.

Heat pumps offer the most energy-efficient way to provide heating and cooling in many applications, as they can use renewable heat sources in our surroundings. Even at temperatures we consider to be cold, air, ground and water contain useful heat that is continuously replenished by the sun. By applying a little more energy, a heat pump can raise the temperature of this heat energy to the needed level. Similarly, heat pumps can also use waste heat sources such as from industrial processes, cooling equipment or ventilation air extracted from buildings.

Normally, compression heat pumps have a limitation for the level of waste heat. Heat only above 70°C is considered as useful heat in electricity-driven heat pumps. Commercially, absorption heat pumps (heat transformer) giving 160°C hot water are in running-condition and it is possible to extend up to 200°C.

Absorption heat pumps are of two types (Herald *et al*., 1996). Type 1 absorption heat basically runs on a chiller cycle. In this type, useful heat source temperature is in between energy source and waste heat temperatures, which is normally near-ambient for e.g. cooling water conditions. The useful heat obtained in this case is about 1.7 times the source heat. The Carnot COP (Coefficient of Performance) (Herald *et al*., 1996) of this system is given by

$$\mathrm{COP} = 1 + \left(\frac{T_{\mathrm{heatsource}} - T_{\mathrm{usefulheat}}}{\mathrm{T}_{\mathrm{heatsource}}} \right) \times \left(\frac{T_{\mathrm{wasteheat}}}{T_{\mathrm{usefulheat}} - T_{\mathrm{wasteheat}}} \right)$$

Type 2 absorption heat pump or Heat Transformer can raise the temperature of waste heat source (say 100°C) to a useful heat at a higher temperature (say 160°C) without using any external energy. The useful heat obtained in this case is a fraction of the available waste heat and balance is rejected in the sink (say 40°C). The Carnot COP of this system (Herald *et al*., 1996) is given by

$$\mathrm{COP} = \left(\frac{T_{\mathrm{wasteheat}} - \mathrm{T}_{\mathrm{sink}}}{T_{\mathrm{wasteheat}}} \right) \times \left(\frac{T_{\mathrm{usefulheat}}}{T_{\mathrm{usefulheat}} - \mathrm{T}_{\mathrm{sink}}} \right)$$

Figs. 3 and 4 show Carnot COP of Types 1 and 2 absorption-heat-pumps respectively at various waste-heat and useful-heat temperature.

By using a vapour absorption chiller, the available waste heat can be utilized to generate refrigeration and the refrigeration capacity will correspond to the

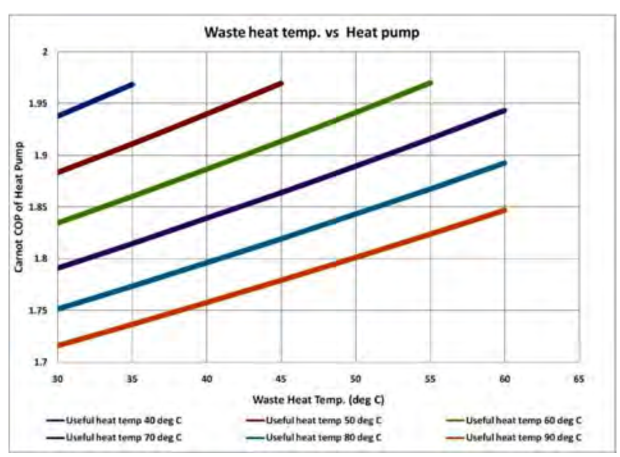

Fig. 3: Carnot COP of absorption heat pump (Type 1)

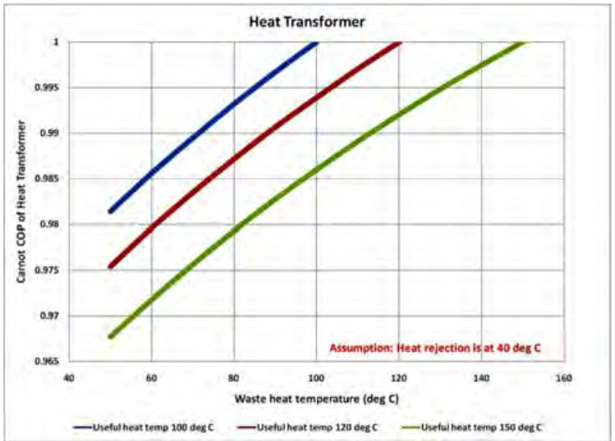

Fig. 4: Carnot COP of heat transformer (Type 2)

COP of the vapour absorption chiller. The actual COP of vapour absorption chiller for various waste heats are provided in Table 2.

Table 2: COP of vapour absorption chiller

S.No.	Temperature of waste heat Deg C	Type of waste heat	Heat recovered down to Deg C	Chiller COP	Chiller type
1	200	Sensible	100	0.7	Single effect
2	350	Sensible	140	1.4	Double effect
3	450	Sensible	190	1.8	Triple effect
4	100	Latent	100	0.7	Single effect
5	140	Latent	140	1.4	Double effect
6	190	Latent	190	1.8	Triple effect

The second concept in WTE is the new Rankine cycle using other than water as a medium. The Organic Rankine Cycle (ORC) is very attractive option used increasingly for generating electricity from low-grade energy. The choice of organic fluids is dependent on the number of parameters such as temperature of the waste heat source, ambient temperature, turbine speed and its power generation methodology (direct coupled or connected via gear box), toxicity of the fluids, availability of the organic fluids and their ODP and GWP (ozone depleting potential and global warming potential).

Organic fluids offer many advantages over steam/water to harness such low potency/low quantity waste heat. A comparison of the TS diagram (temperature entropy diagram, Fig. 5) of a typical organic fluid with water would illustrate the following advantages.

(1) ***Evaporation at low temperature:*** Organic fluids evaporate at a very low temperature. The saturation pressure of R245fa is 18.25 bar at a temperature of 118^{o}C whereas for water the saturation pressure is 1.86 bar at the same temperature. This means that for a waste heat source of about 130^{o}C, the organic fluid vapour can be generated at sufficiently high pressure to run a Rankine cycle for power generation. However, for water with 1.86 bar saturation-pressure at 118^{o}C, the Steam Rankine Cycle is not a technically viable option. An ORC is more viable for generating power from low temperature waste heat streams.

(2) ***Lower heat of evaporation than water:*** The heat required for evaporation or the latent heat of evaporation at a temperature, is very low for organic fluid than water. For example at 118^{o}C, the latent heat evaporation of R245fa is 115 kJ/kg; while for water, this is 2207 kJ/kg. Lower the latent heat of evaporation, higher is the heat recovery due to lower pinch problem. Hence, supercritical ORC (latent heat of evaporation is zero) offers better 'heat recovery efficiency' than even standard ORC.

(3) ***Positive slope of vapour line:*** The vapour line of most of the organic fluids, has a positive slope while vapour line of water has a negative slope. While expanding in a turbine or an expander, the organic fluid becomes more and more super-heated whereas the steam becomes more and more wet (higher super heat is not possible while recovering heat from a low potency waste heat). Hence, the isentropic efficiency of organic fluid turbines is higher than that of steam turbines. Also, erosion-problems caused by liquid droplets during the last stage of steam turbines do not exist in organic fluid turbines.

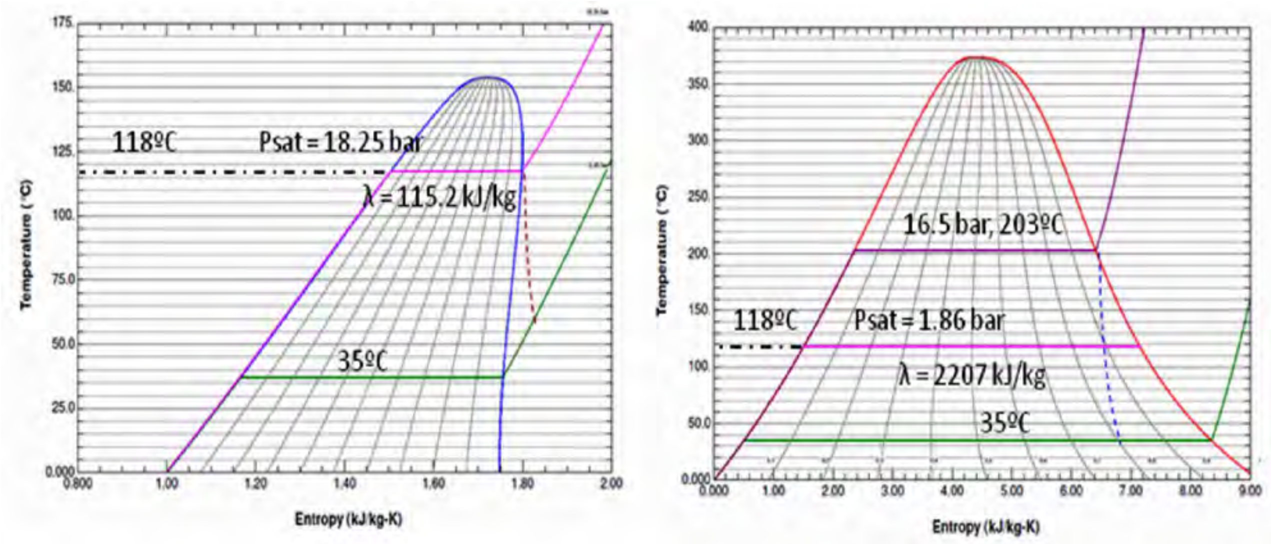

Fig. 5: TS diagram of R245fa and water (NIST 2013)

(4) ***Higher density:*** The density of the most organic fluids is about 12 to 16 times higher than that of steam at the same temperature. For example, the density of R245fa is 111.6 kg/cu.m and the density of steam is 8.3 kg/m^3 at 188ºC. This results in a very compact system.

Hence, ORC has many advantages over conventional Steam Rankine Cycle for generating power from low potency (temperature) heat.

India needs to undertake leadership in this technology space since the large number of small and medium enterprises consuming very expensive primary energy resource exerts that extra strain on the already stretched India's energy security. Hence, the development of some of the technologies such as ORC and heat pumping systems are very important milestones. Thermax Limited, a technology company that focuses on energy and environment has initiated a pioneering effort in this field by building world class heat pumping systems using LiBr-H2O, NH-3-H2O, multi-salt systems, and adsorption-based cooling systems. These have been built over the years involving an enormous amount of indigenous efforts.

Innovative products such as waste heat to cooling, combined heating and cooling, heat transformers, tri-generation systems have been built and deployed in different sectors. Also, Thermax has developed ORC-based waste heat to electricity systems with capacities ranging from 30 kW onwards. The indigenously built ORC systems provide huge opportunities for adapting these new power cycles in the waste to energy mission of the country.

Fig. 6 shows an indigenously developed 100 kWe ORC power skid which has the capability to use waste heat at temperatures as low as 120ºC.

Fig. 6: Indigenously developed 100 kWe power skid

These technologies need a huge impetus from the policy makers to increase their presence and funding since such technologies are the immediate need of the hour.

Conclusion

Waste to energy technology, is an important field of energy science and technology and is a part of larger challenge of process optimization using pinch technology and resource optimization. The potential for saving energy is enormous as evident from the savings in TOE (tons of oil equivalent) and power generation based on the industrial waste energy emission data. WTE can generate additional energy without use of additional fossil energy, which makes it a very attractive technological option in the energy sustainability dialogue.

The heat pumping technologies (for cooling and heating) and the ORC-based power generating technologies are the two foundation stones of the WTE field. There are multiple science and engineering disciplines involved in this with heat transfer as the major focus for technology development. Enhanced heat transfer surfaces, innovative heat cycles, rotor dynamics, power electronics, material science and corrosion are a few areas which merit attention in the WTE field.

In the growing space of renewable energy, the integration of WTE with solar energy and bio energy will further aid in the development of waste energy to sustainable energy systems. Concentrated solar thermal technologies integrated with WTE cycles can result in very high conversion efficiency as well as improving the reliability of the systems.

There are many groups both in academia and industry who are working in this vital field. Thermax Limited is working on both the above concepts and taking up a leadership position in both absorption-based heat pumping and ORC systems. It has built an impressive array of technologies around these two concepts and also integrated waste heat with renewable energy resources such as solar, biomass and even geothermal energy resources.

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