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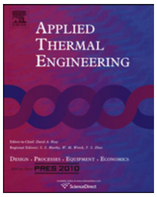

Low-grade waste heat recovery for simultaneous chilled and hot water generation

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ABSTRACT

An investigation of heat recovery from industrial processes with large exhaust gas flow rates, but at very low temperatures, was conducted. Heat recovered from a gas stream at 120 °C was supplied to an absorption cycle to simultaneously generate chilled water and hot water to be used for space conditioning and/or process heating. With the steep increase in energy costs faced by industry, it may be possible to use previously unviable techniques. At nominal conditions, 2.26 MW of heat recovered from the waste heat stream yields a chilled hydronic fluid stream at 7 °C with a cooling capacity of 1.28 MW. Simultaneously, a second hydronic fluid stream can be heated from 43 °C to 54 °C for a heating capacity of 3.57 MW. Based on the cost of electricity to generate this cooling without the waste heat recovery system, and the cost of natural gas for heating, savings of \$186/hr of operation may be realized. When extrapolated to annual operation with a 75% capacity factor, savings of up to \$1.2 million can be achieved. The system requires large components to enable heat exchange over very small temperature differences, with the largest component being the waste heat driven desorber. Minor increases in heat source temperature result in substantial reductions in heat exchanger size.

1. Introduction

This study investigates the feasibility of utilizing waste heat from industrial processes for the purpose of generating chilled water and hot water to be used for space conditioning and/or process heating applications. Numerous industrial plants in the USA and worldwide release large volumes of hot exhaust gases, with representative flow rates from single plants at a site with several plants being as high as 800 Nm^3/sec. Such exhaust gases are typically mixtures of process gases at temperatures as high as 960 °C, but diluted with ambient air at a representative nine-to-one ratio. At such dilution rates, the exhaust stream is available at a nominal temperature of 120 °C. It is clear that this waste heat stream is a very low grade heat source, bordering on the limits of feasibility for utilization in an absorption cycle. Although it is noted that the waste stream may have a heat content of up to 80 MW, this would require cooling the 120 °C stream to such a low temperature (~37 °C) that it would not serve as a heat source along much of this temperature profile from 120 °C to 37 °C.

The objective of the present study, therefore, is to evaluate whether sources of such low grade heat can in fact be recovered in a beneficial manner. In view of the substantial projected worldwide increase in industrial production over the next 15 years, coupled with the steep increase in energy costs currently being faced by industry, previously unviable techniques might be used now to advantage. In addition, the current concerns about global climate change and the environment are constantly leading to increasingly stringent requirements about emissions as well as source energy utilization efficiencies. This background serves as a favorable setting for the investigation of the feasibility of heat recovery through an absorption system.

2. Operational envelope

Industrial operations of the same global corporation often operate over a wide range of capacities and are also sited in diverse locations with ambient temperatures ranging from −30 °C to 35 °C. This wide range of ambient conditions and waste heat capacities leads to the selection of ammonia–water as the working fluid instead of Lithium Bromide-Water, which is more commonly used in large tonnage commercial chillers. Furthermore, the low grade heat source dictates the use of a simple single-effect cycle. Multiple-effect cycles yield higher coefficients of performance (COPs) [1–7]; however, they require higher temperature heat sources. There is also a “half-effect” cycle [8] for specialized low grade applications, but the additional complexity and capital investment of that cycle might preclude its use. Based on these considerations, a single-effect ammonia-water cycle is investigated here to accomplish the following:

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- Generate a chilled water stream at approximately 7 °C, to be used for building and office space cooling
- Use the reject heat from the condenser and absorber to generate a hot water stream that could be employed for building water heating needs, either in standalone mode, or to supplement dedicated water heaters

It is expected that if successful, the eventual implementation of such a system will increase overall process efficiencies, reduce the need for electrically driven air-conditioning and chilling equipment, reduce plant operation costs, and assist industrial facilities achieve compliance with evolving energy efficiency and emissions regulations.

3. Cycle description

A representative schematic of the basic ammonia-water single-effect cycle is shown in Fig. 1. (It should be noted that this schematic represents one basic set of connections between the various components. Alternate connections between components, such as varying absorber and condenser coolant flows from series to parallel and vice versa can also be considered, depending on the details of the application, without changing the basic configuration of the ammonia-water cycle.) Referring to Fig. 1, the absorber saturated outlet condition is represented by state (1), with the subcooled outlet being state (2). This concentrated solution flows through the solution pump and exits at state (3). The solution is then recuperatively heated to state (4) at the desorber inlet. The corresponding saturated state at the desorber inlet is represented by state (21). Thermal energy is provided to the concentrated solution stream in the desorber using the waste heat gas stream entering at state (19) and leaving at state (20). The dilute solution (7) and vapor (6) streams exit the desorber. The vapor stream flows through the rectifier, yielding concentrated ammonia vapor (8) and a reflux stream (9). The reflux stream combines with the dilute solution exiting the desorber and yields the solution at state (16), which enters the solution heat exchanger.

Cooling for the rectifier is provided by a fluid entering at state (28) and exiting at state (29). This coolant could be air, glycol-water solution, or the concentrated solution exiting the absorber. The purified vapor is condensed in the condenser, with the saturated liquid state depicted by state (10) and the subcooled liquid outlet represented by state (11). Cooling for the condenser is provided by a fluid entering at state (22) and exiting at state (23). The ammonia exiting the condenser (11) is recuperatively cooled to state (12) in the refrigerant pre-cooler to reduce its enthalpy at the expansion valve, thereby increasing the cooling capacity. The ammonia then flows across the expansion valve, entering the evaporator as a two-phase mixture at state (13). The cooling load is provided to the evaporator by a stream entering at state (24) and leaving at state (25). The ammonia exits the evaporator as a two-phase mixture (14) of a higher quality and at a higher temperature than at the evaporator inlet due to the temperature glide induced by the residual water fraction in the ammonia. Upon exiting the evaporator, the ammonia flows through the refrigerant pre-cooler, receiving the heat rejected by the condenser outlet stream, and leaves the pre-cooler at state (15). This ammonia stream flows to the absorber, where it is combined with the returning dilute solution (17) from the solution heat exchanger, yielding a two-phase mixture at state (18). As this mixture flows through the absorber, the vapor phase is absorbed into the liquid phase due to heat rejection to the coolant entering at state (26) and exiting at state (27), thus completing the cycle.

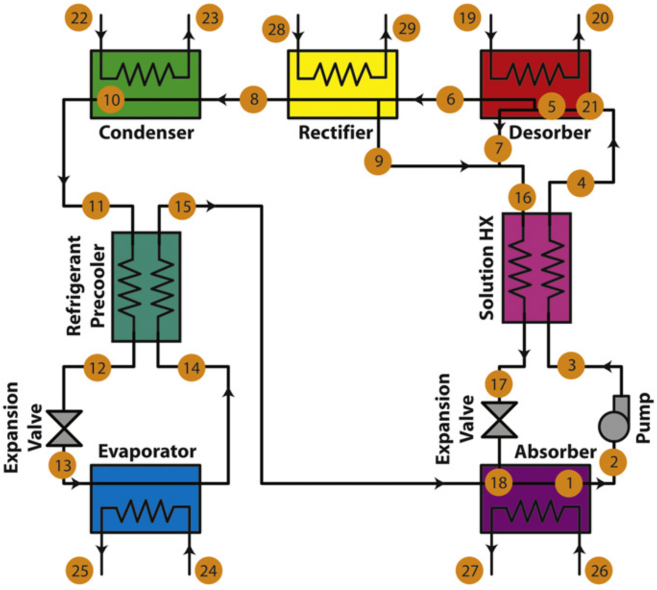

Fig. 1. Absorption cycle schematic.

Mass, species and energy conservation equations are solved for each component shown schematically in Fig. 1 on the Engineering Equation Solver [9] platform. Such conservation equations are well established in the literature, with representative absorption cycle component modeling procedures documented in detail in textbooks such as Herold et al. [10]. In addition to these thermodynamic balances, heat and mass transfer resistances in each component are addressed by specifying representative values of overall heat transfer conductance *UA* (desorber, condenser, absorber) or heat exchanger effectiveness ε (refrigerant pre-cooler and solution heat exchanger). It should be noted that these specifications are necessarily of a single-point type, and represent a first-order analysis of the overall system. However, they do capture, in adequate measure, the driving potentials required for the interactions between the streams exchanging heat and/or mass, and also the effects of irreversible heat exchange between the source/sink and the working fluid across the temperature differences that represent realistic component performances. Representing components with varying thermal capacities by a unique value of *UA*, ε or closest approach temperature difference *CAT* constitutes an approximation to facilitate a preliminary estimation of system performance.

4. Design conditions, choices and assumptions

On the basis of the above information, the design conditions and a baseline system layout were selected. The system has the following features. The waste heat gas stream is assumed to be directly coupled to the desorber. This choice was made instead of first exchanging heat between the gas stream and a heat transfer fluid, which would then supply the heat to the ammonia-water mixture in the desorber. This is because such an intermediate heat transfer loop would introduce a temperature drop between the source and the absorption cycle, and is therefore not an optimal choice in instances such as the present case where the source temperature is already very low. A waste gas stream inlet temperature of 120 °C was chosen, at a flow rate of 945 kg/s. It is also assumed that for this investigation of feasibility, the properties of this fluid are well represented by those of air at similar conditions. This inlet temperature is in fact one of the critical parameters in this project. Even small changes in this temperature affect the system