Geothermal Resources Council Transactions, Vol. 25, August 26-29, 2001

Continual Removal of Non-Condensable Gases for Binary Power Plant Condensers

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Keywords

Binary, condenser efficiency, non-condensable gas removal

Abstract

A membrane-separation system for continual removal of non-condensable gases from binary plant condenser vapor has been proposed. Bench-scale testing of candidate membranes demonstrated that efficient separations were possible for isopentane and isobutane working fluids. In addition, an analysis of actual plant condenser pressure data was performed to quantify the benefits of the system. A conceptual design of the system based on the plant data analysis and membrane test results suggests that the system would be small and inexpensive (relative to increased power generation). The USDOE Office of Conservation and Renewable Energy has funded the construction and testing of a full-scale prototype of this device. Fabrication and host-site testing arrangements are now in progress.

Background

The presence of non-condensable gases (NCGs) in a vapor condensing on a cold surface is known to degrade heat transfer coefficients and raise condenser pressure. From a theoretical viewpoint, the NCG accumulates at the vapor/liquid interface, restricting movement of the vapor toward the interface and lowering the partial pressure of the vapor at the interface. These effects account for the decreased heat-transfer coefficient and higher condenser pressure. When the condenser serves to provide a low-pressure sink for turbine exhaust, the end result is higher turbine back-pressure and reduced turbine output. This is a well-known problem in direct flash steam geothermal plants, resulting from dissolved NCGs in the geothermal brine. A significant portion of steam input is used to drive the NCG removal system, resulting in reduced power output, considering the steam energy flow. While less extreme than direct-flash cycles, binary plants also have NCGs in their working fluid vapors and lose power to the resulting elevated condenser pressures. In cold weather, sub-atmospheric condenser pressures can lead to in-leakage of air, while during normal operation NCGs may be introduced by the turbine lubricant treatment and recycle system. Binary plants are equipped with systems that are used intermittently to purge NCGs from their condensers. These usually employ refrigerated condensers to allow recovery of some of the working fluid from the purged mixture. The frequency and duration of purges varies among different plants, depending on both the rate of NCG accumulation and the plant's operating procedures. The scatter-plot in Figure 1 shows the condenser pressure in an isopentane binary plant as a function of time over a two-month period. The pressure is presented as the difference between actual condenser pressure and the vapor pressure of the working fluid at the condenser outlet temperature.

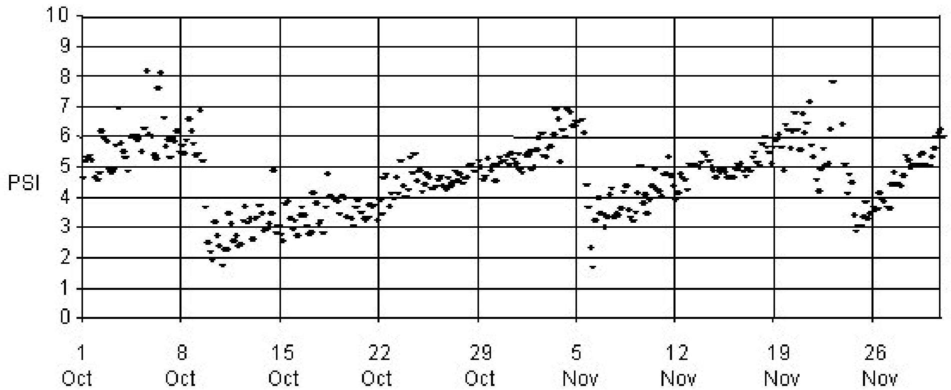

Figure 1. Condenser NCG partial pressure (psi) versus time in days.

The data indicates a gradual buildup of NCG in the plant secondary system that occurs over about one month, at which time the NCG overpressure reaches its administrative limit of 6% to 7% and the condenser is purged. When the NCG pressure drops to about 2 psi, purging is stopped and accumulation begins again.

While it seems intuitive that this increase in turbine back pressure must result in decreased plant power, variation of the other conditions that also affect turbine power output, like brine flow rate, make quantitative interpretation of the data in this graph somewhat difficult. To derive a better relationship between condenser pressure and turbine output, a cross-correlation of plant power as a factor of condenser pressure and brine energy input was performed. The analysis was based on approximately 1-1/2 years of operational data from the same plant that provided the data shown in Figure 1. The results of this analysis show that the effects of brine energy input (mainly brine flow rate) and condenser pressure can be separated. The correlation of plant output and condenser pressure is shown below in Figure 2. The correlation coefficient derived from this data is -26 kW/psi, indicating that almost 1% of plant output is lost per 1 psi increase in condenser pressure. Goodness-of fit and coefficient of determination parameters generated in this analysis strongly support the proposed model, which treated plant output as independent linear functions of brine heat input and condenser pressure. The coefficient of determination (R^2) indicated that more than 98% of the variation of plant output could be explained by this simple linear model.

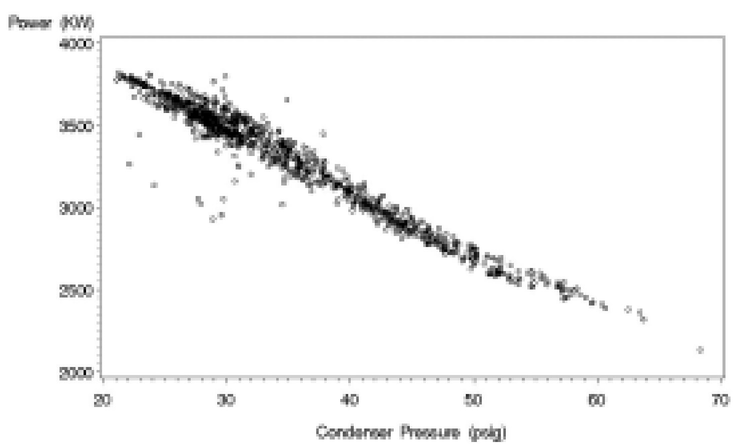

Figure 2. Plant output (kW) as a function of total condenser pressure (psig)

Figure 1 indicates that condenser overpressure due to NCGs increases linearly from 2 to 7 psi between condenser purges. This suggests that the average NCG pressure is about 4.5 psi, and the resulting average loss of power is 117 kW, a yearly loss of 10^6 kWh. A system that would reduce the condenser NCG overpressure to a constant 1 psi would save almost 800,000 kWh of this loss.

From these results, it appears that a low-cost system that could keep the condenser NCG overpressure under 1 psi would be quite effective in increasing plant sales and revenue, especially considering the trend of increasing power prices that the US is currently experiencing. By "low cost" we mean below $75K purchase price, easily installed, with low continual power requirements (say, several hp, equivalent to 0.8 kW/hp), and operated automatically with minimal maintenance.

The Proposed Continual NCG Removal System

Separation of chemically dissimilar compounds, in situations where complete separation is not required, can sometimes be accomplished efficiently with permeable membranes, provided that one or more membranes can be found that take advantage of the component dissimilarities to effect the separation. In the case of mixtures of air and condensable hydrocarbons, differences in both solubility in specialized polymers and molecular size can be used to separate these species. Membrane Technology and Research, Inc. of Menlo Park, CA has been developing such membranes since the early '80s. These membranes have been specifically targeted at separating volatile organic compounds (VOCs) from air, and commercial applications of this technology are growing. The membrane material is based on polydimethylsiloxane (PDMS – the material used in "Silly Putty"). Permeation through the membrane is strongly dependent on the solubility of the component in the membrane, and condensable organic compounds are preferred. Even lighter organic compounds like methane and ethane, as well as the non-condensable air constituents, are restricted from permeating the membrane. This may have practical value, as some operators have suggested that cracking the working fluid to these light hydrocarbons could be a source of non-condensable gases in their systems. "Hyflon,"a new membrane being developed by MTR, is based on a glassy polymer and preferentially permeates smaller molecules, such as air components, in preference to the larger condensable VOCs. In a subcontract to INEEL, both of these membranes were tested by MTR to evaluate their ability to separate nitrogen from isobutane and isopentane. The first series of tests were performed with stamp-size membrane samples in order to determine basic membrane properties for these separations. A second series was performed with small spiral-wound modules to test membrane performance in a commercial-style configuration. In all tests, both membranes showed a high selectivity, favoring the expected permeate. Tests of the PDMS module showed a selectivity favoring the VOC of 10 to 20, depending on the VOC concentration and fraction recovery. The Hyflon tests showed a selectivity favoring nitrogen ranging from about 8 to 20, again depending on the air concentration and fraction recovery. In both cases, the results were interpreted as suitable to achieve the target performance of the NCG removal system.

NCG-Removal System Design

Based on the membrane tests, conceptual separation system designs were generated. The data in Figure 1 was combined with system volume, working-fluid inventory, and air solubility in the working fluids to estimate the rate of NCG introduction into the system, which then determined the throughput requirements for the removal system. The membrane system was specified to operate with a VOC (working fluid) concentration in the vented air-rich stream of no greater than 50% and to keep the concentration of air in the condenser vapor to 1% or less.

Two systems were proposed for further study; one based solely on the PDMS membrane and the other using a PDMS module followed by a Hyflon module. The hybrid system involving both kinds of membranes appears to be most attractive because it will help counteract the tendency of the PDMS module to preferentially retain nitrogen and permeate some oxygen. A single PDMS module would result in elevated oxygen levels in the condenser vapor relative to nitrogen. However, this oxygen concentration would level off at less oxygen than the found in the condenser when it is operating above 2% total NCG content under the current NCG removal scheme, so it would not be expected to cause corrosion or flammability issues.

A diagram of a single-PDMS module system is shown below (Figure 3). The calculated vacuum pump size and membrane area needed to achieve the design requirements are small, compared to typical industrial membrane units. In fact, the system is even small compared to the trial units that membrane manufacturers provide to potential customers to evaluate the membrane use for new applications. For the plant that provided the Figure 1 data, the estimated system parameters are 0.4 m^2 of membrane area and a 0.08 hp vacuum pump. These figures were generated assuming that it was permissible to vent a 50:50 mixture of air and working fluid. More stringent release limits, dictating vent gas that was 80% air increase the system requirements to 0.6 m^2 membrane area and a 0.1 hp vacuum pump. Practically speaking, the system may have to be oversized because fractional-horsepower compressors (vacuum pumps) meeting the requirements for this application do not appear to be available – 7.5 hp is the smallest suitable compressor identified, to date.

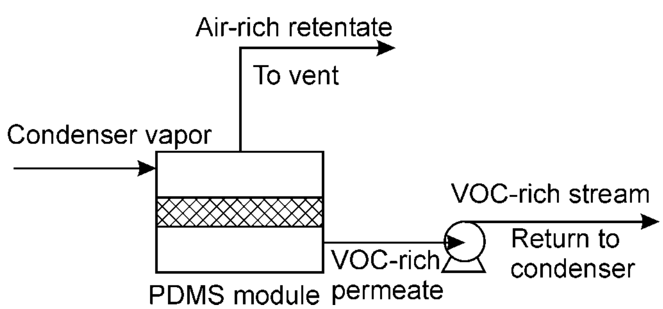

Figure 3. Single-module membrane NCG removal system.

The hybrid PDMS/Hyflon system is shown in the diagram below (Figure 4). As was the case for the single PDMS module system, membrane area and compressor needs are modest: 0.4 m^2 of each membrane and 0.2 (total) compressor power for 50% air in the vent and 1.4 m^2 of PDMS membrane, 0.3 m^2 of Hyflon membrane, and 0.3 (total) compressor power for 80% air in the vent. Three compressors may be needed for the hybrid system, which is unfortunate because compressors are expensive (about $8K each for the 7.5hp compressors used in the price estimates). The possibility of manifolding a single compressor coupled with vacuum/pressure reservoirs will be considered in the upcoming design of the prototype test unit.
Estimated costs for these systems, including design and margin run from under $60K for a 4MW plant to less than $100K for a system size appropriate for a 25-MW plant. Operating and capitalized membrane replacement costs total about $6K/yr for the 4-MW size and $10K/yr for the 25-MW size. These costs assume that one compressor can serve the hybrid system. If not, another $16K initial cost will be added to each size hybrid system.

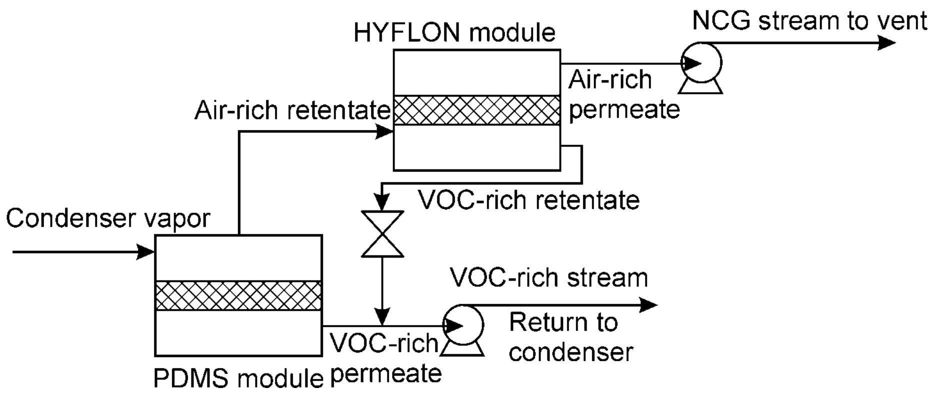

Figure 4. Hybrid two-module NCG removal system.

Development Plans

The USDOE Office of Conservation and Renewable Resources has earmarked funds this year to construct and install a prototype unit. Several plant operators have expressed interest in hosting the prototype tests. Because of the small size, hence portability, of the unit, more than one prototype test may be planned. Testing is expected to begin in early fiscal year 2002 (Fall, 2001) following installation this summer. Some operators have investigated accumulation of NCGs in their air-cooled condensers and have concluded that the NCGs are not distributed evenly throughout the condenser. This will be investigated further to determine an optimal withdrawal point for the vapor/NCG mixture to be sent to the separation system. Additional information on this phenomenon is being sought.

Acknowledgements

This work was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy under DOE Idaho Operations Office Contract DE-AC07-99ID13727. Such support does not constitute any endorsement by the U.S. Department of Energy of the views expressed in this publication. The geothermal community has been very supportive of this investigation. The author would like to express their appreciation to the management and personnel of several binary power plants who have provided useful input to our investigation and to Membrane Technology and Research, Inc. for membrane testing and conceptual system design. Jeff Einerson of the INEEL performed the statistical analysis of plant power data.