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Flashing Liquid Expander Energy Reduction in Refrigeration Systems

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ABSTRACT

Expansion valves in refrigeration systems can be replaced with a flashing liquid expander (FLE) to reduce the energy consumption. The original application, pioneered by J.J. Brasz, was for commercial 500 Ton chillers. A reduction in compressor power of 7-8% was obtained (Hays and Brasz, 1996). Some 100 of these chillers have been operating for more than 10 years.

Recent emphasis on the use of environmentally benign refrigerants for cold storage and freezers has created a renewed interest in energy savings. Some refrigerants such as ammonia and propane have high lifts which result in increased inefficiency due to the isenthalpic expansion valve. Useful power is dissipated and the frictional heating results in generation of less liquid for the evaporator. Advances in FLE technology have been made which enable confidence in the use of two-phase impulse turbines for refrigeration and other applications. Performance measurements of FLE expanders and experience in several applications are presented

Analysis of the power reduction for the above refrigerants and R134A was conducted for a range of variables using proven efficiency of FLE units. The results are presented both for the use of external seals and for the use of canned generators which enable a sealess expander. Increases in the coefficient of performance (COP) were determined and are presented.

A case study of a large ammonia refrigeration system and cogeneration system is presented utilizing the measured FLE efficiencies and canned generators. The electric power generated was 410 kW. The increase in liquid fraction after the flash was 9.9%. An increase in COP of 31% resulted.

This paper substantiates advances in two-phase impulse turbines to enable designers to utilize this type of FLE to improve refrigeration system performance. The results of the analysis are presented in a form to enable estimation of energy savings for the above refrigerants.

1. INTRODUCTION

Refrigeration systems with Joule Thomson expansion valves are ubiquitous throughout the world. Over 3 billion systems are installed worldwide. They require a huge amount of energy. A recent estimate of the energy consumption was over 3,000,000 Gigawatt hours per year (Field, 2014). The use of isenthalpic expansion valves in the vapor compression cycle can result in wasted energy of 10-20% of the system power. Efficiency can be improved by the use of two-stage compression systems or cascading at the cost of additional complexity and expense. However, the single stage compression cycle is the most common in use. If a near isentropic expansion were available efficiency would be improved and energy conserved. The addition of a near isentropic expander to the refrigeration cycle can improve the efficiency of a single stage cycle to the level of more complex arrangements.

Investigation and development of flashing liquid expanders has continued for several years. Beginning in the 1970's and continuing to the present many types of expanders have been investigated. These include positive displacement machines, (Yu et al., 2015), (Smith et al., 1999), (Weiss, et al., 1975); Tesla turbines, (Steidel and Weiss, 1976); Turgo turbines (Aaraj, et al., 2014); radial inflow expanders (Swearington and Faber, 1986), (Dambach, 2010); and two-phase impulse turbines, (Elliott, 1982), (Welch et al., 2011). Of the various concepts only the two-phase impulse turbine has been commercialized in significant numbers. Other concepts rely upon expansion of the two-phase mixture in a centrifugal force field – leading to separation of the liquid phase from the driving vapor phase. Concentration of the liquid phase on the wall with a minimal surface area can lead to slip and frictional losses.

(Apfelbacher, 1989), (Gulich, 1981). The radial inflow machines can also suffer from forcing the liquid to flow in an adverse centrifugal force field, leading to erosion and vibrations (Clevenger and Tabakoff, 1975).

The successful results with two-phase impulse turbines led to the adoption and deployment of that technology in commercial chillers and other applications. Several applications of the two-phase impulse turbine were successfully addressed, including the replacement of expansion valves in chillers and industrial applications. The two-phase impulse turbine reached the level of efficiency ($>70\%$) and reliability (over 100 machines in chillers) to enable realization of the advantages of a near isentropic expansion in refrigeration systems. Other FLE machines can also be used if this level of efficiency and reliability is reached. This paper will focus on experience with two-phase impulse turbines and results of the application of this type of FLE to refrigeration systems will be provided.

The two-phase impulse turbine uses a two-phase nozzle that is based on work originally performed at the NASA Jet Propulsion Laboratory (Elliott and Weinberg, 1968). At the inlet the fluid may be liquid, two-phase or a supercritical fluid. As the fluid travels down the converging-diverging nozzle (see figure 1) the pressure drops and more vapor begins to form. The best working fluids have a low surface tension and viscosity. These properties allow small droplets, typically on the order of 10 microns, to be sheared from the liquid body by the accelerating vapor. A small droplet size is crucial for allowing the vapor and liquid phases to couple together well. If the two phases are not coupled and the gas slips around the liquid droplets which are traveling at a lower speed; friction is generated which harms the turbine and cycle efficiency. The nozzle is the thermodynamic conversion element. Expansion of the two-phase flashing mixture is made to occur in a linear geometry, avoiding collection of the liquid on the wall.

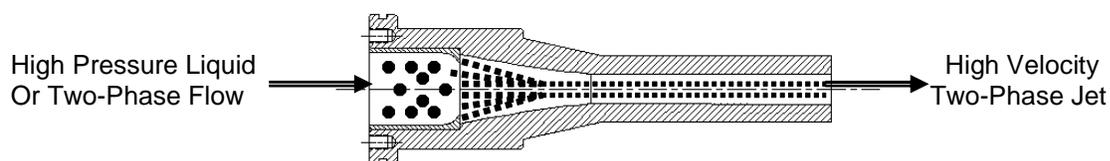


Figure 1: Cross-Section of the Two-Phase Converging-Diverging Nozzle.

The turbine itself is a single-stage axial impulse turbine. Because the flow is two-phase a high mass flow can be achieved with a low jet velocity. This enables a relatively low-speed turbine such that a gearbox is not necessary. A low jet velocity also reduces the potential for erosion and is well below the erosion threshold for steel or titanium, which are currently used. Experience with commercial chillers showed that under some expansion conditions the jet velocities are even below the erosion threshold for aluminum. The two-phase mixture exits the nozzle and enters the axial impulse turbine passages (figure 2). Provided that the liquid droplet size is small, a large fraction of the droplets follow the gas phase in turning through the blade passages. Less liquid actually impacts the blades which is desirable because such impacts and the resulting flow of the collected liquid results in some frictional loss. The liquid on the blades transfers energy to the moving blade and leaves the blades at the exit.

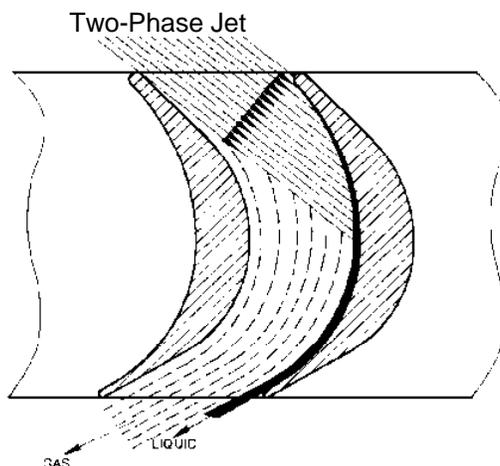


Figure 2: Axial Impulse Turbine for Two-Phase Flow.

Packaging the nozzles and rotor into a useful device is illustrated by figure 3. In this application the two-phase impulse turbine is installed on the compressor motor shaft. The power generated by the turbine reduces the required motor power.

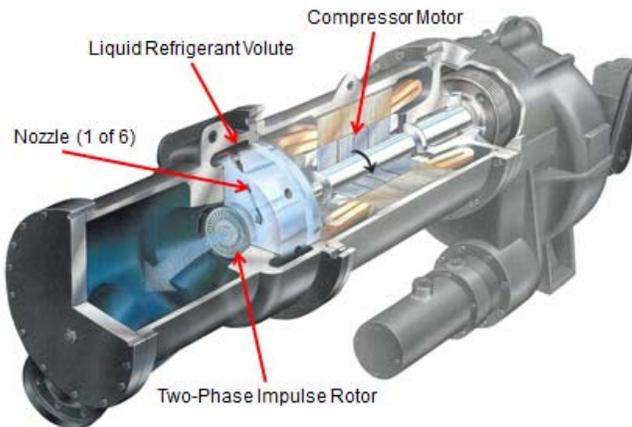


Figure 3: Installation of Two-Phase Impulse Turbine in Centrifugal Chiller

Two-phase impulse turbines have been applied to refrigeration, waste heat power cycles and geothermal power cycles. The commercial chiller application is shown in figure 4. A two-phase impulse turbine generator in a waste heat recovery system is shown in operation in figure 5.



Figure 4: Commercial Chiller with Two-Phase Impulse Turbine Installed



Figure 5: Two Hundred Kilowatt (200kW) Two-Phase Impulse Turbines Operating with R245fa

The measured efficiencies are summarized in Table 1. On the basis of the performance measurements for the two-phase impulse turbines an efficiency of 74% was used in the calculations. For a unit with an air cooled generator, a generator efficiency of 95% was assumed. For a canned generator a quoted generator efficiency of 83.3% was used in the calculations.

Table 1: Summary of Two-Phase Turbine Efficiency, Measured and LNG Performance Code

Application	Fluid	Power	Number of Units	Efficiency	Comments
Refrigeration (Carrier, 1995)	R134A	15 kW	>100	55%	Carrier 19XRT. In operation for 10+ years
Refrigeration (Douglas Energy, 1996)	R134A	15 kW	1	64%	Laboratory test improvements of blade profiles
Air Separation (Welch 2006)	LN ₂	1.1 kW	1	76%	R&D Tests
Waste Heat Binary Cycle (Welch, 2012)	R245fa	172 kW	1	74%	Mitsui factory tests. (off design)
Waste Heat Binary Cycle (Hays, 2016)	R245fa	227 kW	1	65% at U/C of .32 80% projected for U/C of .48	Mitsui ship trials. (off design)
Geothermal Power (Hays, 2010)	R134A	1242 kW	1	73%	U.S. DOE program. (off design)
J-T Valve Replacement (Hays, 2009)	LNG	1660 kW	1	85% from design code	ConocoPhillips design study

2. Performance Calculations

A schematic of the single stage cycle analyzed is shown in Figure 6. The compressor receives dry vapor flow from the evaporator. The compressed vapor is condensed in the condenser. The saturated liquid is flashed in either an expansion valve or in the FLE generating power. The mixture of cold vapor and liquid flows to the evaporator. The vapor fraction from the FLE is lower than that from the expansion valve; therefore more liquid is available to flash in the evaporator, increasing the refrigeration capacity.

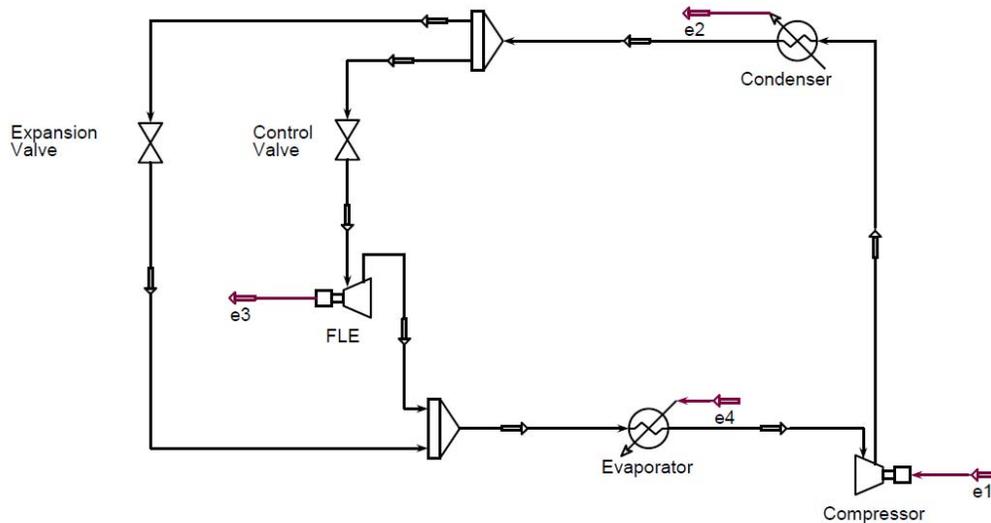


Fig 6: Schematic of Application of a Flashing Liquid Expander to a Refrigeration System

$$\text{The compressor power was determined to be } e1 = \dot{m} (h_o - h_{isc}) / \eta_{comp} \quad (1)$$

Where \dot{m} = mass flow rate
 h_o = inlet enthalpy to compressor
 h_{isc} = isentropic enthalpy rise in compressor
 η_{comp} = compressor efficiency (= 70% for calculations)

$$\text{The FLE shaft power is } e3 = \dot{m} \eta_{FLE} (h_1 - h_{isFLE}) \quad (2)$$

Where η_{FLE} = FLE efficiency (=74% for calculations)
 h_1 = inlet enthalpy to FLE (saturated liquid)
 h_{isFLE} = isentropic enthalpy at exit of FLE

$$\text{The evaporator heat absorption with the FLE is } e4' = \dot{m} (h_o - h_{FLE}) \quad (3)$$

Where h_{FLE} = enthalpy at exit of FLE = $x_v h_{vFLE} + (1-x_v) h_{lFLE}$
 x_v = vapor fraction at exit of FLE
 h_{vFLE} = enthalpy of vapor at exit conditions of FLE
 h_{lFLE} = enthalpy of liquid at exit conditions of FLE

$$\text{The evaporator heat absorption with the expansion valve is } e4'' = \dot{m} (h_o - h_1) \quad (4)$$

Neglecting line pressure drops and pressure drops in the condenser and evaporator gives the Coefficient of Performance of the refrigeration system with the FLE (COP') as:

$$\text{COP}' = e4' / (e1 - e3 \eta_{\text{gen}}) \quad (5)$$

Where η_{gen} = electric generator efficiency

The Coefficient of Performance for the refrigeration system with expansion through the expansion valve (COP'') is:

$$\text{COP}'' = e4'' / e1 \quad (6)$$

The ratio of COP' / COP'' was determined for R134A, Ammonia and Propane, for the simple refrigeration system considered, as a function of evaporator temperature for several condenser temperatures. The value of FLE efficiency can be used for more complex systems and considering pressure drops to determine the benefit for those cases.

Figures 7, 8 and 9 provide the results for the air cooled generator and the sealess generator.

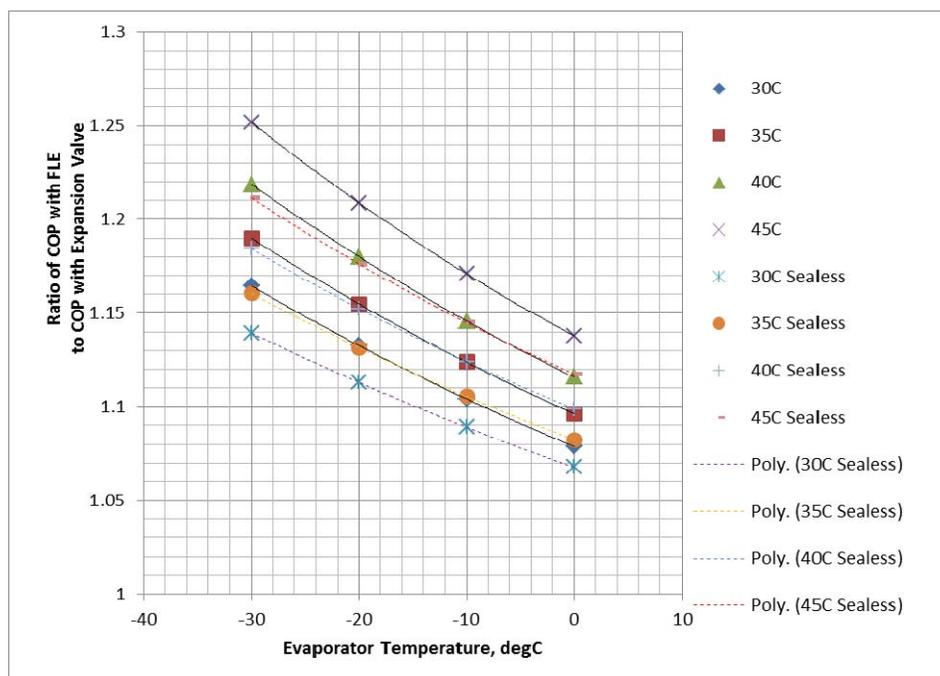


Figure 7: Ratio of COP with FLE to COP with Expansion Valve for R134A versus Evaporator Temperature for various Condenser Temperatures

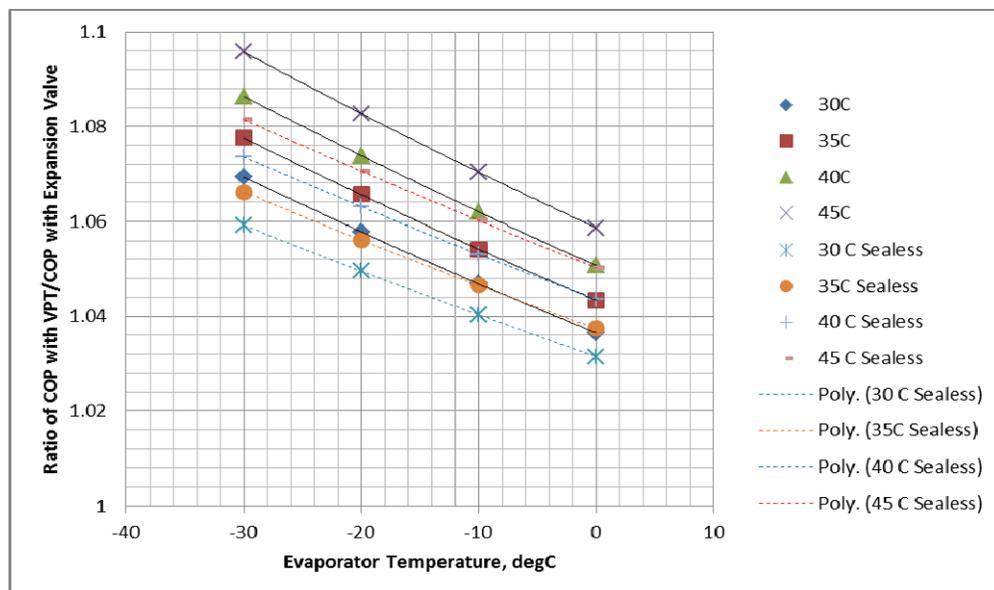


Fig 8: Ratio of COP with FLE to COP with Expansion Valve for Ammonia versus Evaporator Temperature for various Condenser Temperatures

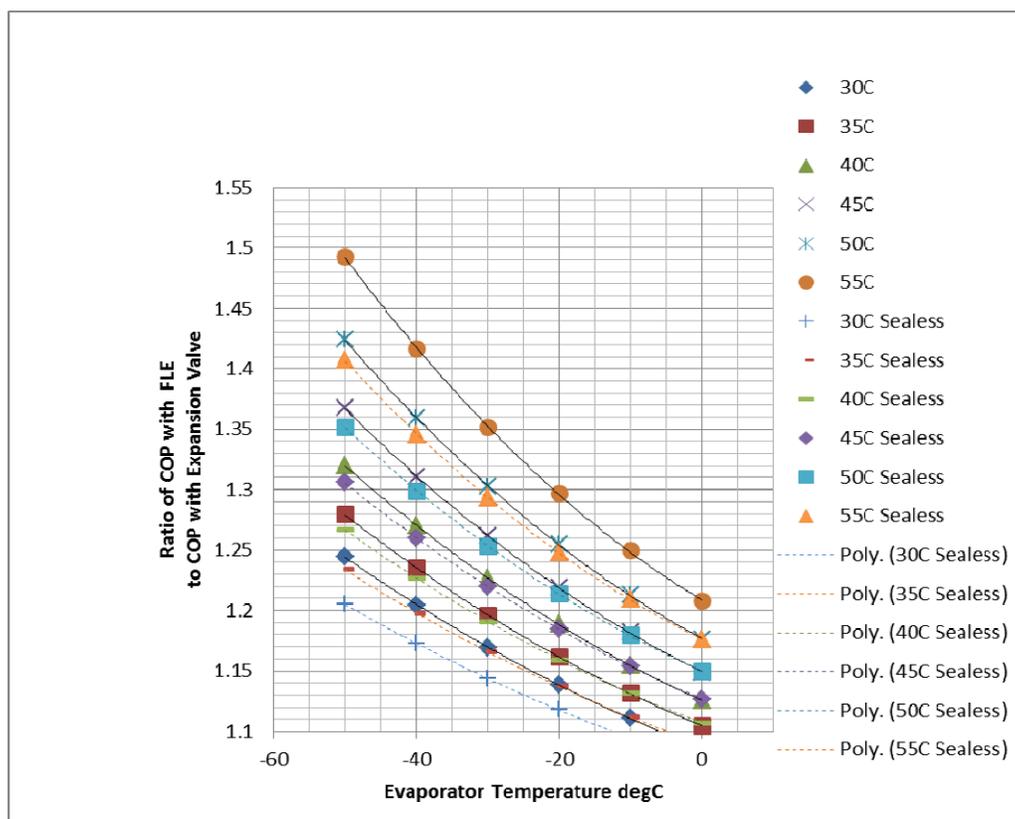


Figure 9: Ratio of COP with FLE to COP with Expansion Valve for Propane versus Evaporator Temperature for various Condenser Temperatures

The R134A and propane can be seen to have the most gains for large lifts, ranging from 10-25% for R134A and from 10%- 50% for propane. The energy savings for simple ammonia cycles is less, 5-10%, but still significant. Determination of the advantages of the FLE for other refrigerants or cycles can be made using the efficiency of 70-75% for the expander and using the methodology of equations (1) – (6).

The use of a sealess generator was also analyzed. An efficiency of 83% was utilized for the generator electrical efficiency. In these cases the generator losses are absorbed by the refrigerant resulting in somewhat less liquid in the expansion.

As expected, the use of the lower efficiency generator reduces the advantage of the FLE somewhat. However the range of improvement is still 10-20% for R134A and 10-40% for propane. Ammonia decreased to 4-8%.

3. Application to Cogeneration Refrigeration System

The application of FLEs to a combined cogeneration refrigeration system was examined. A schematic of the refrigeration portion is shown in Figure 10.

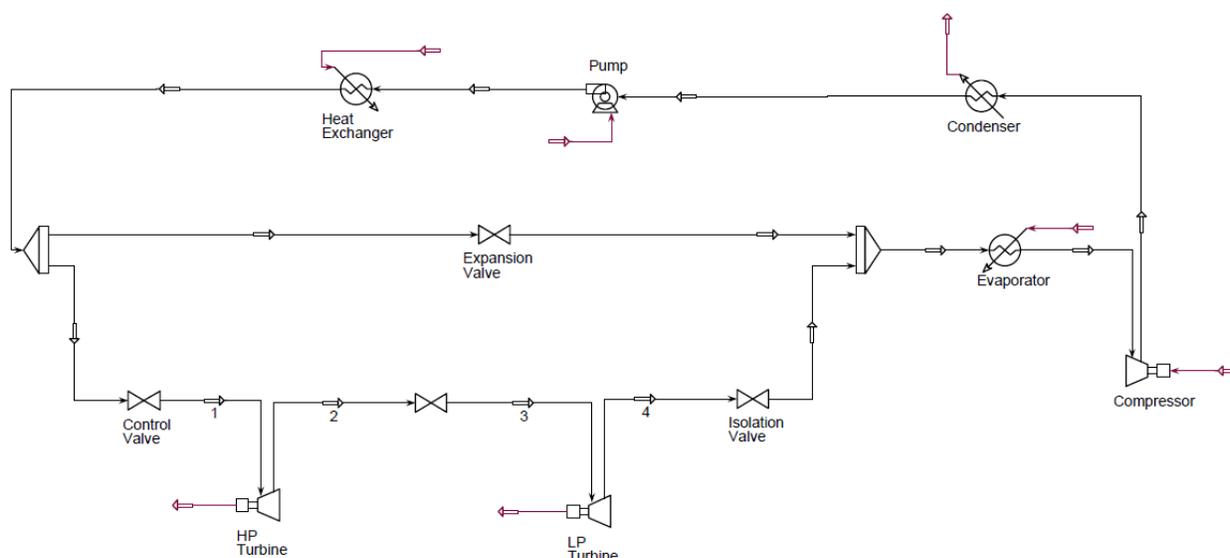


Figure 10: Schematic of Ammonia Refrigeration Circuit in Cogeneration System

The application considered is a combined cogeneration and refrigeration plant. The ammonia compressor consumes 2,625 kW. Refrigerant condensate is pumped to a pressure of >51 barA. The ammonia is heated by heat rejection from a part of the cogeneration plant to 90C. Because of the large pressure ratio, two FLE units in series are required. The high pressure (“hp”) FLE expansion was from 50.9 barA to 4.5 barA. An allowance of .15 bar was made for the pressure drop in the piping connecting the hp FLE to the low pressure (“lp”) FLE; resulting in an inlet pressure of 4.35 barA expanding to 1.013 barA,

The two FLE expanders are arranged in series, paralleling the expansion valve. If a turbine is off-line the control system automatically closes the turbine inlet valve and opens the expansion valve, ensuring non-interruptible operation of the refrigeration system. The electric power output of the turbines can be connected directly to the

compressor motor or input to the facility power system, reducing the external load.

The design code resulted in an hp turbine efficiency of .737 and an lp turbine efficiency of .606. Applying a value of .833 for the canned generator efficiency to the turbine shaft output gives process efficiencies of .614 and .504 for the hp and lp turbines respectively. The total power produced by the FLE units is 410 kW. The increase in liquid flow is 9.9%. The increase in liquid flow results in an increase in the evaporator cooling capacity from 4,108 kW to 4,515 kW. Thus the increase in COP is:

$$\text{COP}' / \text{COP}'' = [4,515 / (2,625 - 410)] / [4,108 / 2,625] = 1.31$$

FLEs with air-cooled generators and dry gas seals and a seal gas system can also be supplied. Reliability may be lower. The cost would be comparable. With the higher generator efficiency the total FLE power would be 473 kW. The increase in liquid fraction increases the evaporator capacity to 4,594 kW. The increase in COP is:

$$\text{COP}' / \text{COP}'' = [4,594 / (2,625 - 473)] / [4,108 / 2,625] = 1.37$$

4. CONCLUDING REMARKS

Energy savings in refrigeration systems is now possible for retrofits with flashing liquid expanders or for incorporation of the expander in new systems. Development and demonstration of high efficiency and reliable two-phase impulse turbines has provided the designer with the tools to reduce energy consumption in simple cycles by as much as 10-50%. Replacement of Joule-Thomson expansion valves in other refrigeration processes can produce meaningful energy savings and increases in liquid product. The application to very high expansion ratios was shown to increase efficiency by 31-37%.

References

- Aaraj, Y., Mortada, S., Clodic, D., and Nemer, M., Design of a Turgo Two-Phase Turbine Runner, *International Refrigeration and Air Conditioning Conference*, Purdue, 2014
- Apfelbacher, R., Hamkins, C., Jeske, H., and Schuster, O., Kreiselpumpen in Turbinenbetrieb bei Zweiphasen-Strömungen, *KSB Technische Berichte 26*, 1989
- Carrier, "ACE" Hermetic 19XT Centrifugal Chillers, Syracuse, 1995
- Clevenger, W. and Tabakoff, W., Erosion in Radial Inflow Turbines, NASA CR 134677, Jan 1975
- Dambach, R., Reliable Criteria for the Selection of Flashing Liquid Expanders, GPA Europe Conference, February 2010
- Douglas Energy Co., Research on Two-Phase Turbines, Placentia CA, 1996
- Elliott, D., Weinberg, E. Acceleration of Liquids in Two-Phase Nozzles, Technical Report TR 32-987, Jet Propulsion Laboratory, California Institute of Technology, July 1968.
- Elliott, D., Theory and Tests of Two-Phase Turbines, *DOE/ER-10614-1* Jet Propulsion Laboratory, California Institute of Technology, March 1982
- Field, C., Intergovernmental Panel on Climate Change Report, United Nations 2014
- Gulich, J., Energierückgewinnung mit Pumpen in Turbinenbetrieb bei Expansion von Zweiphasengemischen, *Sulzer Technical Review, Vol 3*, 1981

Hays, L. and Brasz, J, Two-Phase Turbines for Compressor Energy Recovery, *International Refrigeration and Compressor Conference*, Purdue, 1996

Hays, L., Variable Phase Turbine Design Study, *Final Report for ConocoPhillips*, Energent Corporation, 2009

Hays, L., Demonstration of a Variable Phase Turbine Power System for Low Temperature Geothermal Resources, *Final Report Contract Number DE-FG36-05GO15153*, U.S. Department of Energy 2010

Hays, L., Factory Tests of a 300 kW Two-Phase Turbine for Shipboard Waste Heat Recovery, Energent Corporation, Santa Ana, CA 2016

Smith, I. K., Stosic, N. R. and Aldis, C.A, Twin Screw Expanders in Large Chiller Units. *Proceedings of International Conference on Industrial Compressors and their Systems*, City University, London, September 1999

Steidel, R., and Weiss, H. Performance Test of a Bladeless Turbine for Geothermal Applications, *UCID-17068*, Lawrence Livermore Laboratory, March 1976

Swearingen, J., and Fager, H., Gain of Substantial Low-Temperature Refrigeration and Recovery of Power by the Replacement of J-T Valves with Flashing Liquid Expanders in the LNG Stream to the Storage Vessels, *Eighth International Conference & Exhibition on Liquefied Natural Gas*, Los Angeles, June 1986

Weiss, H., Steidel, R., and Lundberg, A., Performance Test of a Lysholm Engine, *Report UCRL-51861*, Lawrence Livermore Laboratory, July 1975

Welch, P., Tests of a Small Two-Phase Turbine on Liquid Nitrogen, Energent Corporation, Santa Ana, CA, 2006

Welch, P., Boyle, P., Giron, M., & Sells, M. Construction and Startup of Low Temperature Geothermal Power Plants, *Geothermal Resources Council Transactions*, 35, 1351-1356, 2011

Welch, P., Qualification of a 200 kW Two-Phase Turbine for Shipboard Waste Heat Recovery, Energent Corporation, Santa Ana, CA, 2012

Yu, Y., Hu, D., and Wu, F. Applications of the Screw Expander in Geothermal Power in China, *Proceedings of the World Geothermal Congress 2015*, April 2015.

Abbreviations

FLE – Flashing Liquid Expander

COP – Coefficient of Performance, ratio refrigeration energy to required power

COP' – Coefficient of Performance for refrigeration system with FLE

COP'' – Coefficient of Performance for refrigeration system with isenthalpic expansion valve

J-T Valve – Joule-Thomson expansion valve