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# LYSHOLM MACHINES AS TWO-PHASE EXPANDERS

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## ABSTRACT

Power recovery from the expansion of saturated liquids and wet vapours is discussed. Applications in large scale refrigeration systems, and in the recovery of power from low grade heat sources are reviewed. Twin screw machines are well suited for this function and a computer simulation of their operation in this mode is described. Performance estimates are compared with test results carried out by the authors using R113, US investigators using water and Japanese workers using R12 as the working fluid. Agreement at tip speeds of up to 30 m/s is good but mass flow rates are overestimated at higher speeds. Further experimental work is proceeding to resolve this. Adiabatic efficiencies of the order of 80% appear to be possible in large machines.

## INTRODUCTION

The expansion of saturated liquids or wet vapours has been recognised as a potential means of generating power for more than seventy years [1]. Unfortunately, the practical problems of expanding a two-phase mixture efficiently proved an insuperable obstacle. Post world war two interest in geothermal power led to consideration of the use hot pressurised water or very wet steam, emerging directly from natural aquifers, as a power plant working fluid. The normal means of achieving this is to flash the fluid to some intermediate pressure, separate the steam from the vapour, expand the dry steam in a turbine and reinject the separated hot water. In the early nineteen seventies, Sprankle [2] proposed the use of the Lysholm twin screw machine to expand the "total flow" of steam and water to recover power without separation and thereby to increase the recoverable power by 50 - 100%. This stimulated a great deal of investigation of both twin-screw machines and turbines [3-7] as two-phase expanders. The results of these investigations were largely disappointing. Rotor sizes of up to 28 ft diameter were predicted for large scale geothermal power plant using screws while measured adiabatic efficiencies of such machines using water were only of the order of 50%. Performance analysis of these machines was limited largely to parametric studies [8].

Turbines, although smaller, were also found to be relatively inefficient, with water as the working fluid, and maximum predicted efficiencies hardly exceeded 65%. Using organic fluids in a closed cycle, Elliott [3] predicted maximum turbine efficiencies of up to 70%.

Independently, one of the authors considered closed cycle systems with organic working fluids as a means of recovering power from hot water sources in a system similar to that proposed by Elliott but using a twin-screw expander [9]. The system, described as a Trilateral Flash Cycle (TFC) system is shown in Fig 1. The use of organic fluids reduces the size of the expander required by a factor of 10 and the volume ratio

of expansion by a factor of about 100 over that required for water while the efficiency penalty due to heat transfer from the hot brine to the organic working fluid is relatively small due to the nearly reversible heat transfer in the primary heat exchanger. In an initial test programme carried out by the authors using R113 as the working fluid, a peak adiabatic efficiency of nearly 72% was achieved from a small screw expander developing only 25 kW.

An alternative application for two-phase expanders is as a throttle valve replacement in large scale vapour compression plant. Taniguchi et al [10] carried out an extensive analytical and experimental programme with the aim of incorporating such machines in large scale heat pumps for district heating schemes using R12 as the working fluid. Extrapolations were made from small scale test runs at tip speeds of up to 15 m/s which indicated internal adiabatic efficiencies of up to about 80% in units of 250 kW output at tip speeds of 50 m/s. The high speed predictions did not coincide well with our own experimental results.

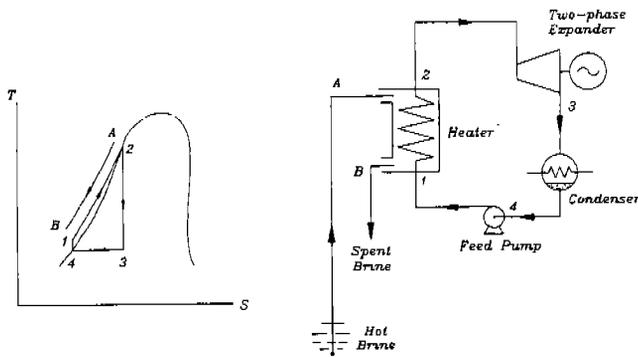


Fig 1a The Process

Fig 1b System Components

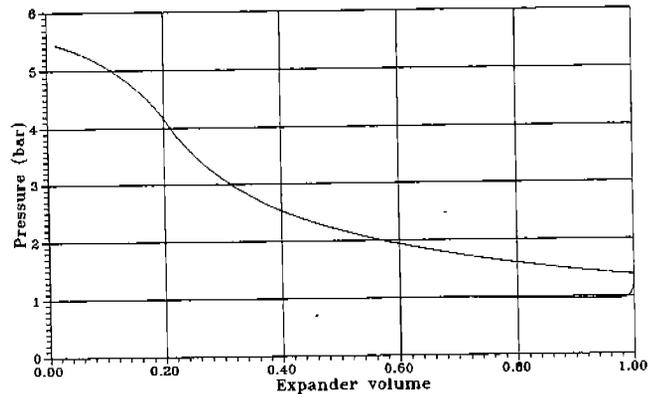
Fig 1 The TFC Power System

The high speed predictions did not coincide well with our own experimental results.

## ANALYSIS OF TWIN-SCREW TWO-PHASE EXPANDERS

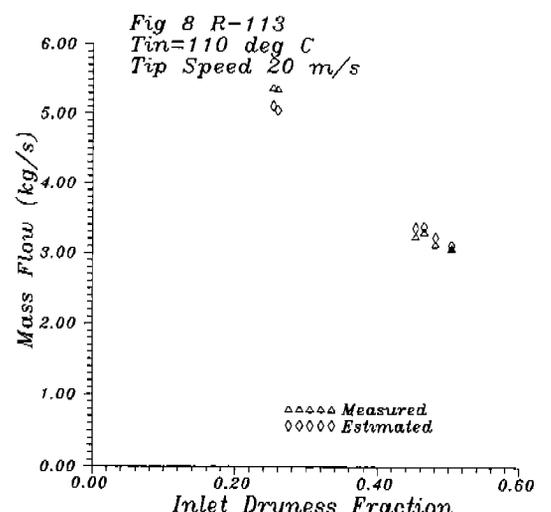
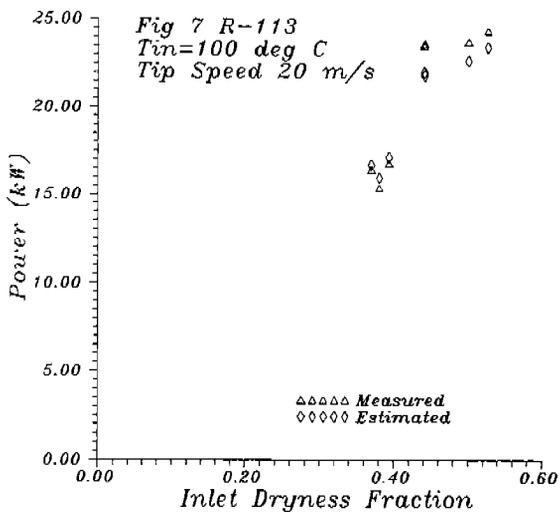
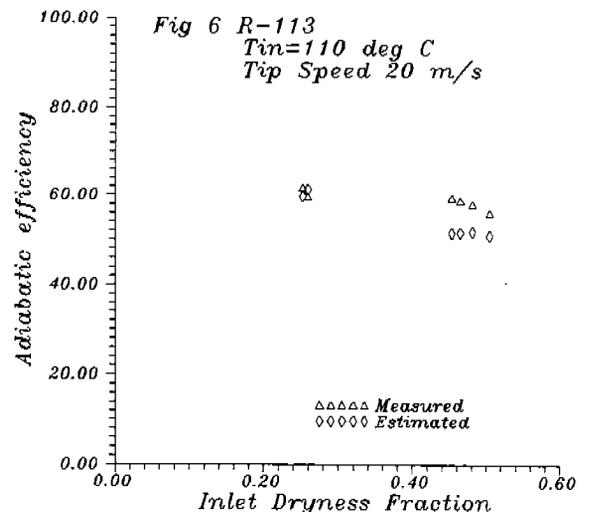
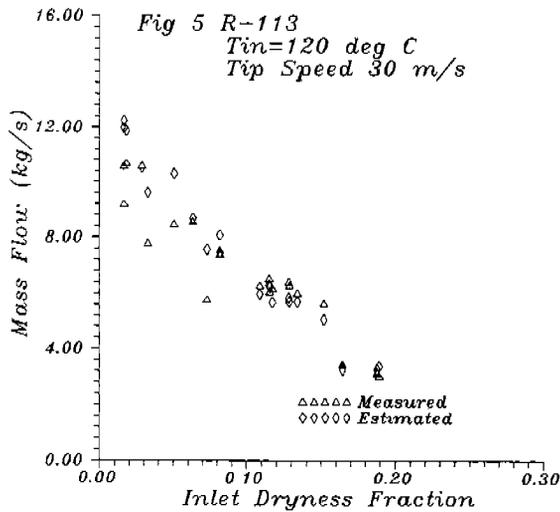
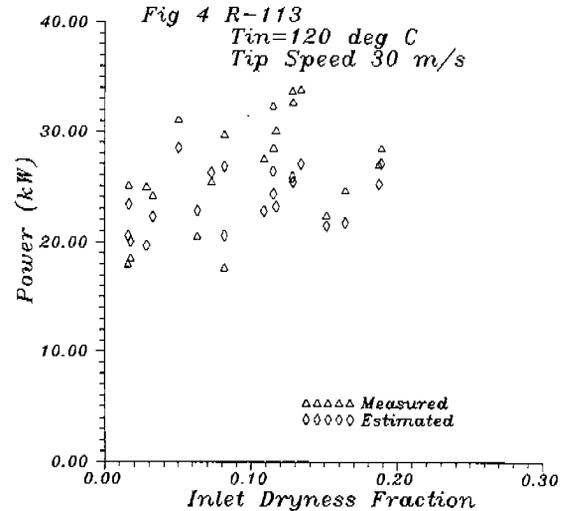
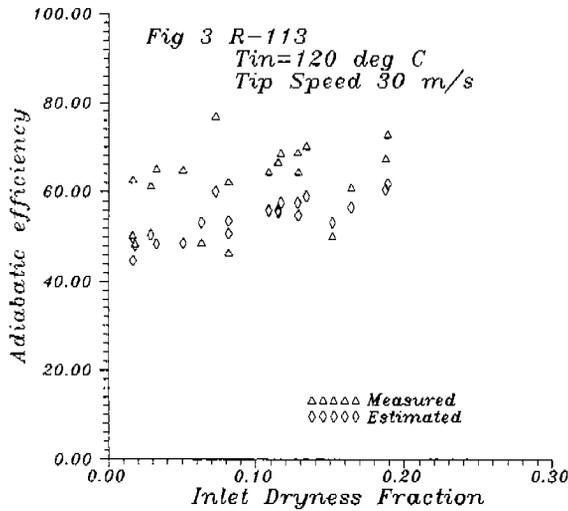
The only partially analysed total flow water test results and their unexplained low efficiencies, discrepancies between the authors' measurements and Taniguchi's predictions and inexplicably lower efficiencies in modified expanders tested by the authors all justified a more fundamental study of screw expander performance in this mode. Accordingly a comprehensive computer simulation of the simultaneous processes which occur within the machine was carried out using techniques already established for screw compressors [11].

Fig 2 Expander p-V Diagram



The analysis was based on the simultaneous solution of the equations of continuity of mass, momentum and energy assuming one-dimensional flow throughout. These were combined with software packages for the estimation of working fluid physical properties and for the main flow and leakage paths between the rotors and between the rotors and casing at any angle of rotation. At each rotor position the volume could therefore be determined and hence the internal energy of the trapped fluid estimated. The corresponding pressure was thereby directly obtained. The solution of the simultaneous set of non-linear

differential equations was then carried out in a separate routine, the result of which was to produce a pressure-volume diagram of the entire expansion process. This approach, although broadly similar to that of



Taniguchi, was applied with greater attention to detail including the consideration of alternative estimates for viscous flow of the two-phase fluid, inclusion of the kinetic energy of the working fluid trapped within the rotors and further refinements which were found to affect performance predictions more extensively than might be thought from simulations of screw performance as a gas compressor.

### RESULTS OF THE ANALYSIS

The most significant finding of the analysis, is the nature of the filling process in the expander. Discharge, its converse in compressors, takes place approximately at constant pressure. The Taniguchi model [10] appears to support this as valid for expander induction. However, in the case of two-phase fluids the density may be twenty or more times greater than that of compressed gas. The pressure drop associated with the local acceleration of the fluid in entering between the rotor lobes is correspondingly greater. In turn, the pressure drop induces flashing of the liquid into vapour and hence even higher fluid velocities. This is shown, together with the remainder of the expansion process, for a typical case in Fig 2. It may be seen that the expansion involved in filling is considerable and it follows that it will increase as tip speeds are raised. The consequences of this are:

- i) that the overall volume ratio of controlled expansion is much larger than that of the machine built-in value,
- ii) a proper account of this effect is required for optimum design without either over or underexpansion within the machine.

Predictions from the model were compared with experimental data obtained from four independent studies including those of the authors. The constraints imposed on the solutions were equality with the experimental inlet pressures, temperatures and fluid dryness fractions, exit pressures and rotational speeds. Test data were obtained from the following expanders all of which had a 6:4 rotor lobe configuration:

| Rotor Diam<br>mm | L/D  | Vol Ratio | Rotor Profile | Working Fluid   | Origin             |
|------------------|------|-----------|---------------|-----------------|--------------------|
| 204              | 1.1  | 5         | SRM A         | Refrigerant 113 | Smith              |
| 204              | 1.1  | 6         | SRM C         | Refrigerant 113 | Smith              |
| 204              | 1.05 | 3         | SRM C         | Refrigerant 113 | Smith              |
| 163              | 1.65 | 3         | SRM C         | Refrigerant 113 | Smith              |
| 128              | 1.28 | 5.3       | SRM C         | Water           | Steidel            |
| 416              | 1.51 | 7.8 - 9.1 | SRM C         | Water           | US Dept. of Energy |
| 81.6             | 1.65 | 5         | SRM C         | Refrigerant 12  | Taniguchi          |

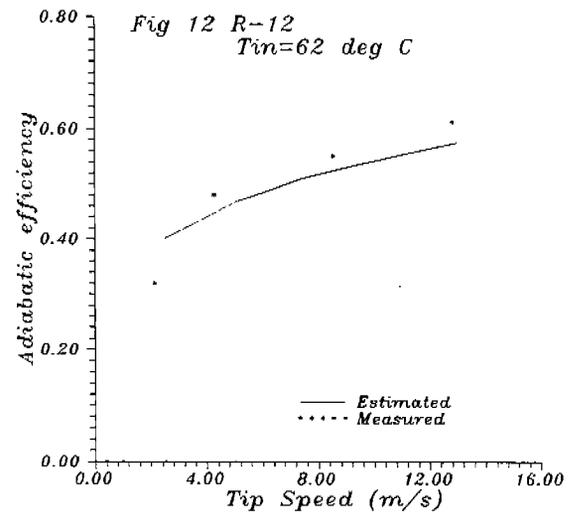
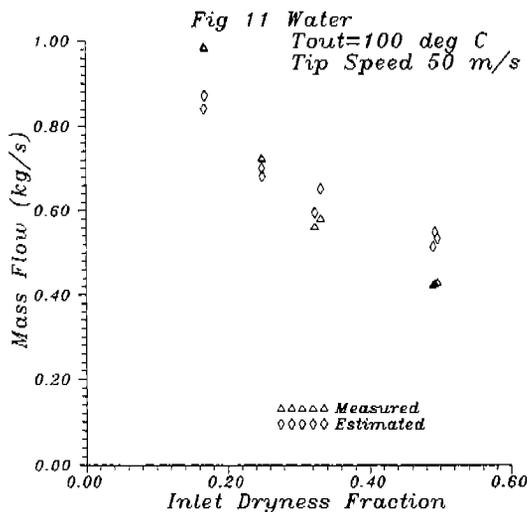
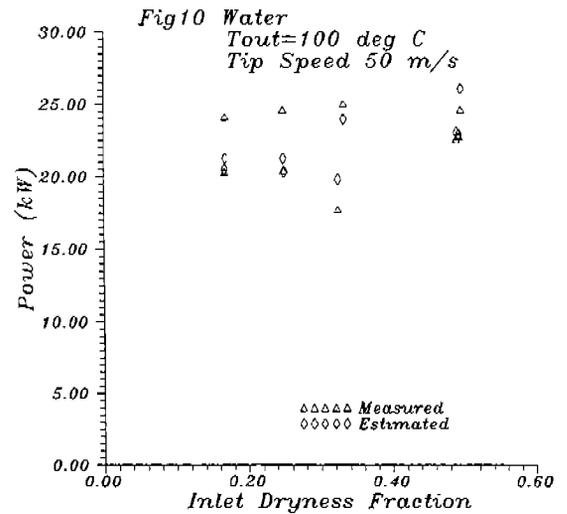
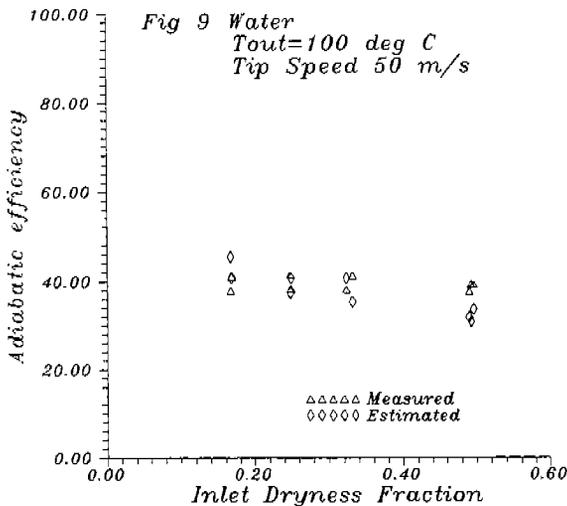
From this data 501 test points were analysed.

Because of the additional variable of dryness fraction, comparison between predicted and measured results requires simultaneous consideration of efficiencies, mass flow rates and power outputs.

A graphical presentation with each of these as ordinate and dryness fraction as the common abscissa shows the degree of agreement most readily. In view of the large number of graphs required, only specimen results which highlight the findings are given. As shown in Figs 3 to 12, at tip speeds up to 30 m/s there is fair agreement between theory and experiment but overall, the predicted performance is slightly less than that actually attained. At higher tip speeds, the agreement is

less satisfactory and measured performance falls off more rapidly than predicted.

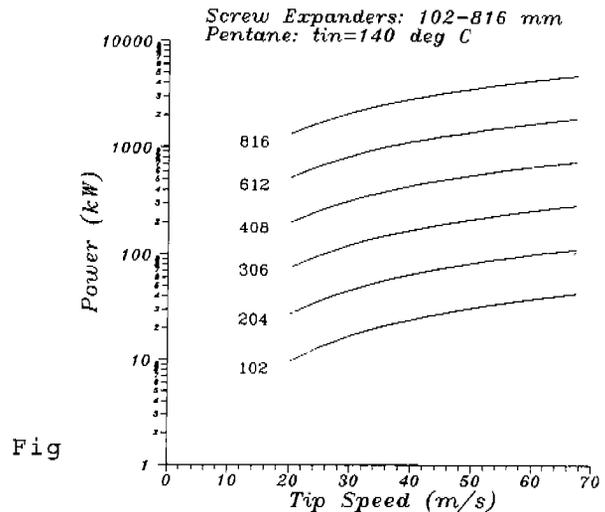
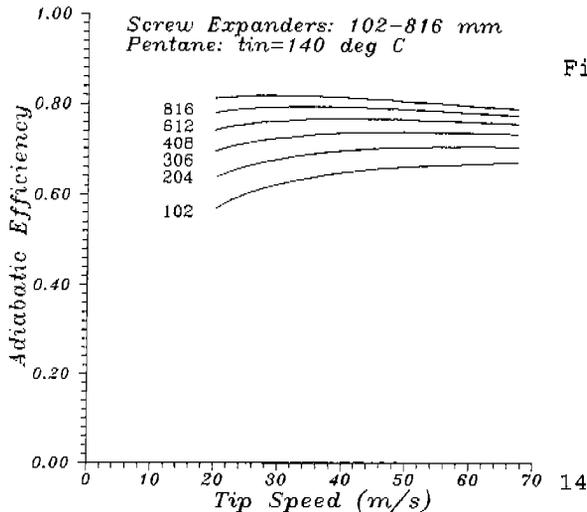
It is interesting to note that both predicted and measured adiabatic efficiencies are much higher with organic working fluids than with water. The reasons for this, which hitherto were not clear, can now be readily explained. This is that due to the relatively high boiling



point of water, its vapour density is very low at expander exit conditions. Under these circumstances expanders with very much higher built in volume ratios are required than those used in the total flow test programme. Thus predicted efficiencies were much higher for water expansion when built in volume ratios of 30:1 or more were assumed.

In view of the large number of assumptions made for the internal processes, the degree of agreement reached over so wide a range of test conditions is encouraging. There is little doubt it could be improved if the comparison were made between the estimated and experimentally derived pressure-volume diagrams. A programme for obtaining pressure-volume measurements, especially during the filling process, is currently being carried out for this purpose.

Additionally, the computer program was used to make estimates of efficiencies and outputs likely from two-phase screw expanders operating at their optimum test running conditions. Typical results are shown in Figs 13 and 14. Despite the known unreliability of the higher speed results, it is clear that adiabatic efficiencies of 70 - 80% should be readily attainable in larger machines.



## CONCLUSIONS

Results of the study described in this report show that the thermodynamic modelling techniques used for gas compressors, can be used with some modification, to make fairly reliable predictions of two-phase screw expander performance. These show the importance of proper prediction of the filling process in the expander. It is also clear from the study that adiabatic efficiencies comparable to those of dry gas compressors are obtainable from twin screw machines operating as two-phase expanders.

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