APPLICATION OF MECHANICAL VAPOUR RECOMPRESSION TO INDUSTRIAL SOLIDS DRYING

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ABSTRACT

A positive result of the oil crisis of the seventies is the realisation of energy's value and the need to use it sparingly. Increasing attention has been focussed on all aspects of industry where fuel oil and gas had played a major role.

Industrial drying, one of the most widely applied unit operations in chemical and process engineering, is a highly energy intensive operation. Studies have identified a number of alternatives for lowering energy consumption in this process through various heat recovery techniques.

Due to the difference in their operating principles steam-heated dryers and air-heated dryers, in most aspects, require different techniques of energy recovery.

This paper examines the feasibility of applying Mechanical VAPOUR RECOMPRESSION (MVR) in recycling the heat in the exhaust vapours of steam-heated dryers. Operating costs of MVR - assisted dryers are compared to those of convetional steam dryers and it is shown that considerable savings can be attained with a payback period of two to three years expected from the considered case study.

INTRODUCTION

Of all the unit operations in chemical and process engineering that of drying has probably the widest application. Most manufacturing operations, particularly in the chemical, food and metallurgical fields entail one of more stages where drying in one form or another is carried out. This is necessary due to the fact that products may be required for use in dry state and, in any case, it is costly to transport the water or solvent contained in "wet" materials.

Drying, from the industrial standpoint is understood to represent the removal of liquid, usually but not always, water from a solid by thermal means resulting into either quite dry product or substantially so. Such a definition clearly distinguishes it from other comparable heat-treating operations such as evaporating, crystallisation, etc. and the strict mechanical dewatering, methods such as centrifugation, filtration, decantation, etc.

A wide variety of dryer designs have been evolved over the years and several attempts have been suggested as to how best to classify them. Broadly speaking most industrial dryers fall into two main categories focussed on the method of heat transfer (2, 7) namely: convection and conduction.

The predominant mechanism is usually convection in direct dryers in which the material id dried by means of a hot gas stream passing over or through it and conduction in indirect dryers in which the material is heated via a wall. There may be significant heat transfer by radiation in either case and some degree of conduction in convection dryers and vice versa. Apart from special types of dryers relying solely on radiation or dielectric heating it is rare for conventional dryer to be operated with pure radiation alone. Examples of direct dryers are spray dryers, flash or pneumatic dryers, fluidised bed dryers and rotary dryers. Examples of indirect dryers are drum dryers, agitated jacketed vessels, heated screw conveyors, rotary steam dryers and paddle dryers.

Drying is a highly-intensive operation. Keey(3) estimates that even with labour-intensive operations, the costs of providing energy rarely fall below one-quarter of the total operating expenses. Furthermore, with continuous plants the energy costs is often over half these running costs. Therefore with the high cost of fuel there is considerable incentive to conserve heat and device methods of using less energy.

Several methods which can be used to conserve heat have been proposed by various workers and these include :

(a) Better care and operation of existing dryers by methods such as:
    (i) avoiding air leaks,
    (ii) proper lagging,
    (iii) proper operation of burners,
    (iv) keeping heat transfer surface areas clean.

(b) Reducing moisture content of dryer feed by the less costly means wherever practical.

(c) Recovery of heat from the dryer exhaust gases which entails such methods as :

    (i) Recirculation of the exhaust gas from convection dryers wherevere practical.

    (ii) Using the exhaust gas to preheat the feed material.

    (iii) Use of heat pump in convection dryer(4). This absorbs heat from the exhaust air and; rejects it to the dryer inlet air.

    (iv) Drying with superheated stead(5) instead of air as the heating medium

    (v) Finally, another approach which has so far not been utilised widely in industry, is that of upgrading the heat in exhaust vapours of indirect dryers and using it for heating.

Energy Recovery by Mechanical VAPOUR RECOMPRESSION in Indirect Dryers

Drying in its crudest form, consumes a lost of energy because apart from the high heat input required to change the state of liquid water to water VAPOUR usually the VAPOUR is thrown into the atmosphere without any attempt to recover its heat content.

In evaporation plants where mechanical VAPOUR RECOMPRESSION has become very popular, the VAPOUR from the evaporator is compressed to attain a higher temperature and then condensed in the heating element of the same equipment and thus cut down the need for steam from external sources. As vapours from an indirect dryer are relatively free of air, which could otherwise lead to very low condensing heat transfer coefficients, (a point which eliminated direct dryers from this study), it is evident that the same principle of recycling heat could be applied to indirect dryers as the case is for evaporators.

This basis of operation of MVR in such a drying process is shown schematically in Fig.1.

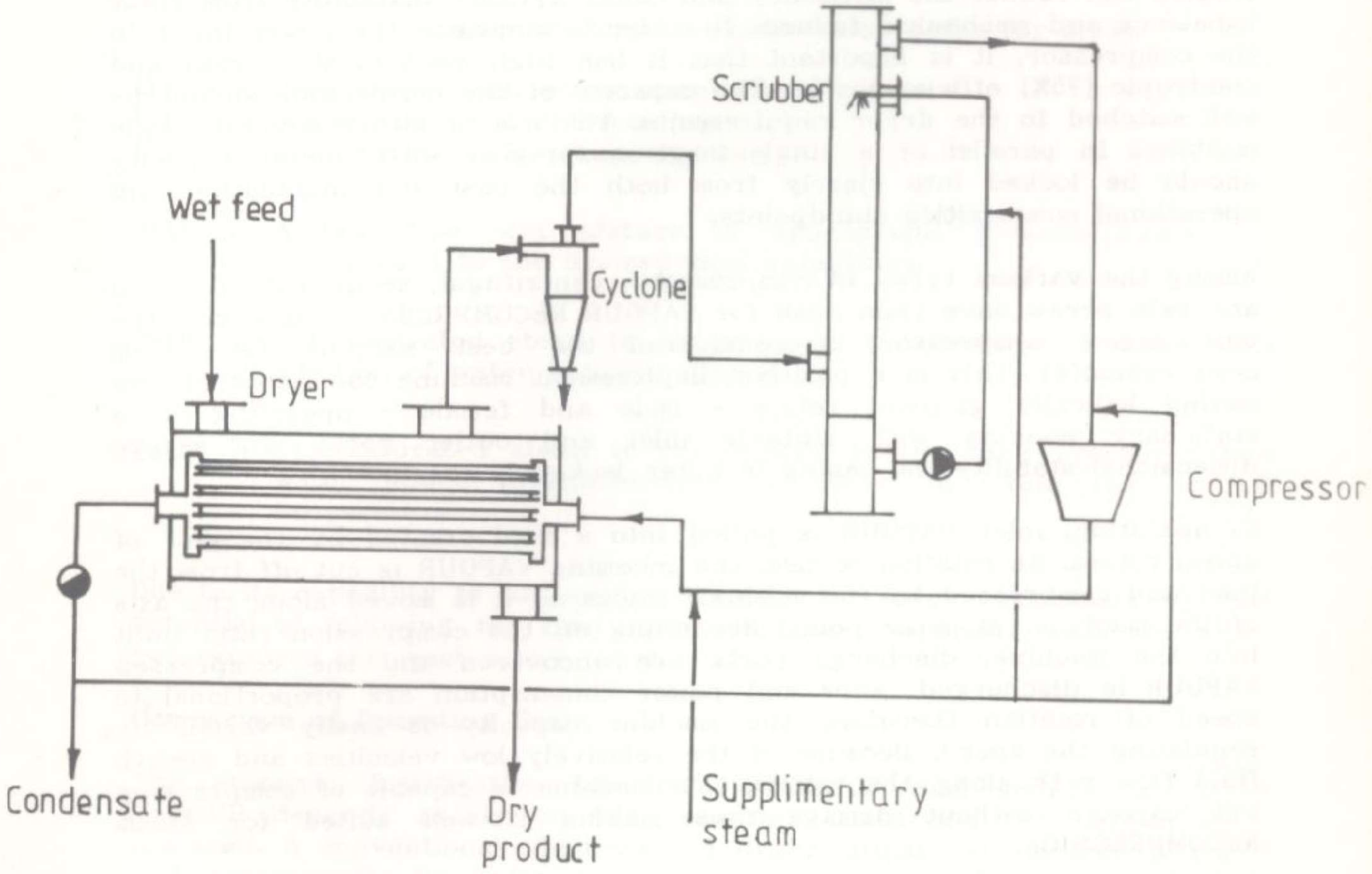

Figure 1: Dryer with Mechanical VAPOUR RECOMPRESSION

Low pressure VAPOUR is drawn from the dryer through a cleaning device such as a scrubber and/or cyclone to remove solid particles, compressed sufficiently for its temperature to exceed the boiling temperature of water in the dryer. The compressed VAPOUR (now high pressure steam) is then passed through the heating element of the dryer-which could be a tube bundle, the vessel jacket or the screw in screw conveyor dryers. The latent heat is thus transferred back to the dryer.

Steam Compression and Choice of Compressor

Several important factors should be considered when selecting a compressor. These include :

- Mechanical reliability
- Efficiency
- Capacity
- Cost.

Many types of compressors availble ususally have some unique operational limitations that have got to be considered when compressing steam. For example, the high impeller tip speeds of centrifugal compressors make them highly susceptible to erosion from entrained liquid droplets. This erosion can reduce the efficiency and cause dynamic instability from rotor imbalance and mechanical failure. In order to minimuze the power input to the compressor, it is important that it has high mechanical (> 90%) and isentropic (75%) efficiencies(5). The capacity of the compressor should be well matched to the dryer requirements. The use of either several single machines in parallel or a single large compressor with enough capacity should be looked into clearly from both the cost and installation and operational complexities standpoints.

Among the various types of compressors, centrifugal, reciprocating, Roots and twin screw have been used for VAPOUR RECOMPRESSION. However, the twin screw compressor is considered the best machine for steam compression(6). This is a positive displacement machine consisting of two mating helically grooved rotors - male and female - operating in a stationary housing with suitable inlet and outlet ports. To assure dimensional stability the casing is water jacketed.

In operation, inlet VAPOUR is pulled into a void created by the pair of spiral rotors. As rotation occurs, the incoming VAPOUR is cut off from the inlet and compressed by the meshing rotors as it is moved along the axis of the machine. At some point, depending on the compression ratio built into the machine, discharge ports are uncovered and the compressed VAPOUR is discharged. Flow and power consumption are proportional to speed of rotation therefore the machine capacity is easily varied by regulating the speed. Because of the relatively low velocities and smooth fluid flow path along the rotors, this machine is capable of compressing wet vapours without damage thus making it well suited for steam RECOMPRESSION.

A number of different thermodynamic paths may be followed during the compression process. Figure 2 shows the possible compression paths for steam in a temperature - entropy (T-S) diagram.

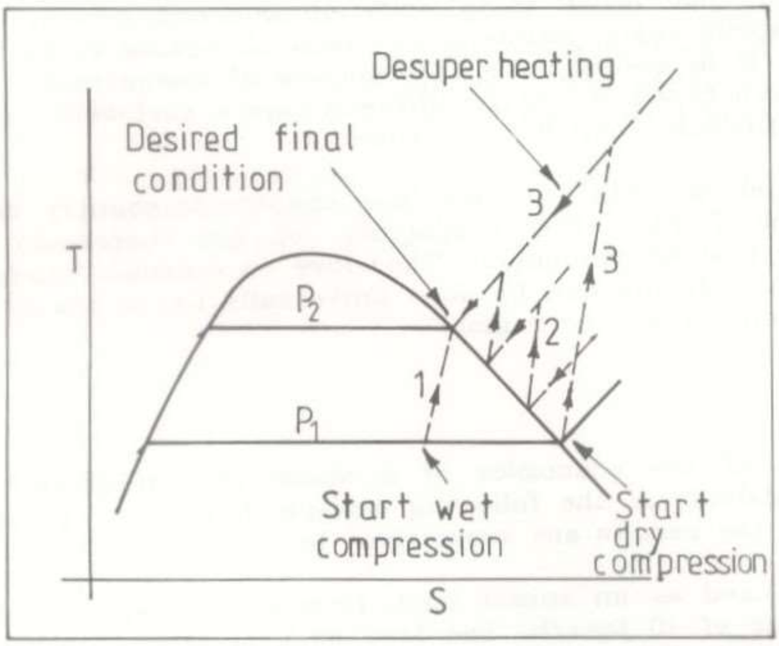

Figure 2: Possible Compression paths for steam

(1) Wet compression with screw compressor
(2) Dry compression with intercooling
(3) Dry compression with desuperheating

Path 1: A two-phase wet mixture of appropriate dryness quality is compressed to the desired final conditions.

Path 2: Dry saturated steam is compressed in a number of stage with addition of water between stages.

Path 3: Dry saturated steam is compressed to the final pressure then water added (desuperheated) in order to attain the desired temperature.

Due to its capability to compress wet steam, the screw compressor has the potential of following the first path which in comparison with the other two requires the least power input.

Comparison of Operating Costs

The economic justification for RECOMPRESSION and recycle of dryer VAPOUR depends mainly on the operating costs and the capital costs involved. A conventional steam-heated dryer utilises steam from a boiler and consequently its major operating cost is that of fuel oil (or gas) to raise steam. An MVR - assisted dryer requires both electricity to run the compressor and a small amount of steam from an external supply to supplement that which comes from VAPOUR RECOMPRESSION. Therefore its operating costs is the cost of the two utilities.

It is appreciated that other costs arise in connection with operation dryers namely labour costs, maintenance costs, electricity costs for other drives, etc., but it is assumed for the purpose of comparison that these are common to both types. A major additional capital cost between the two is that of the compressor and its accessories.

Electricity and fuel oil costs will vary from country to country depending on, among other things, the availability of the necessary natural resources and/or cost of production. Therefore an economic study on the use of MVR-assisted drying can be done universally i.e. it has to be done separately for each country or region.

Case Study

To give an idea of the economics of a steam RECOMPRESSION drying system, the calculations of the following example have been presented in the appendix and the results are summarized here.

Dry spent grain used as an animal feed, from a brewery, say, is to be produced at a rate of 10 tons/h. The feed as a moisture content of 40% and is to be dried to 0.5% moisture. Electricity costs (9) 4.15 Tshs/kWh and fuel oil is solid at 14.33 Tshs/litre (January 1988 prices).

Comparison of operating costs is made between a conventional steam-heated dryer and one assisted by an MVR unit which raises the VAPOUR pressure from 1 bar to 3 bar (abs).

The conventional dryer requires 5345 Tshs/h for fuel oil for its steam supply whereas the MVR-assisted dryer requires 1715 Tshs./h for its 413 kW electricity for the compressor and 703 Tshs/h being the cost of its supplementary steam. This leads to an annual (8000h/year) saving in operating costs of about Tshs 23 million (approx. 230,000 US $. Quotations from suppliers(8) indicate that suitable twin screw compressors and accessories for this job would cost around 500,000 to 700,000 US $, thus a payback period of 2 to 3 years is expected. This will of course be highly affected by the fluctuation of the value of the US $ against the Tsh.

Simulations

Since electricity and fuel oil costs are expected to rise in the future (an observed trend for a long time now) computer simulations for expected savings by the use of MVR-assisted dryers as compared to conventional steam heated dryers have been done as follows :

(i) Annual savings as a function of fuel oil cost for a number of electricity costs.

The results are presented in Fig. 3 and it is observed that :

- the higher the fuel oil cost the more the savings for given cost of electricity
- the higher the electricity cost the lower the savings for a fixed fuel oil cost

- there is a minimum fuel oil cost for each given electricity cost below which the use of MVR becomes non-profitable (i.e. negative savings). These minimum fuel oil cost values have been extrated from Figure 3 and plotted against the cost of electricity Figure 4. Figure 4 reveals a linear relationship :

  $Y = 1.210\ x +0.272$ i.e. NVR operation in this case study is only profitable if the cost of fuel oil, Y, is more than $1.21\ x + 0.272$ Tshs/1 where X is the cost of electricity in Tshs/kWh.

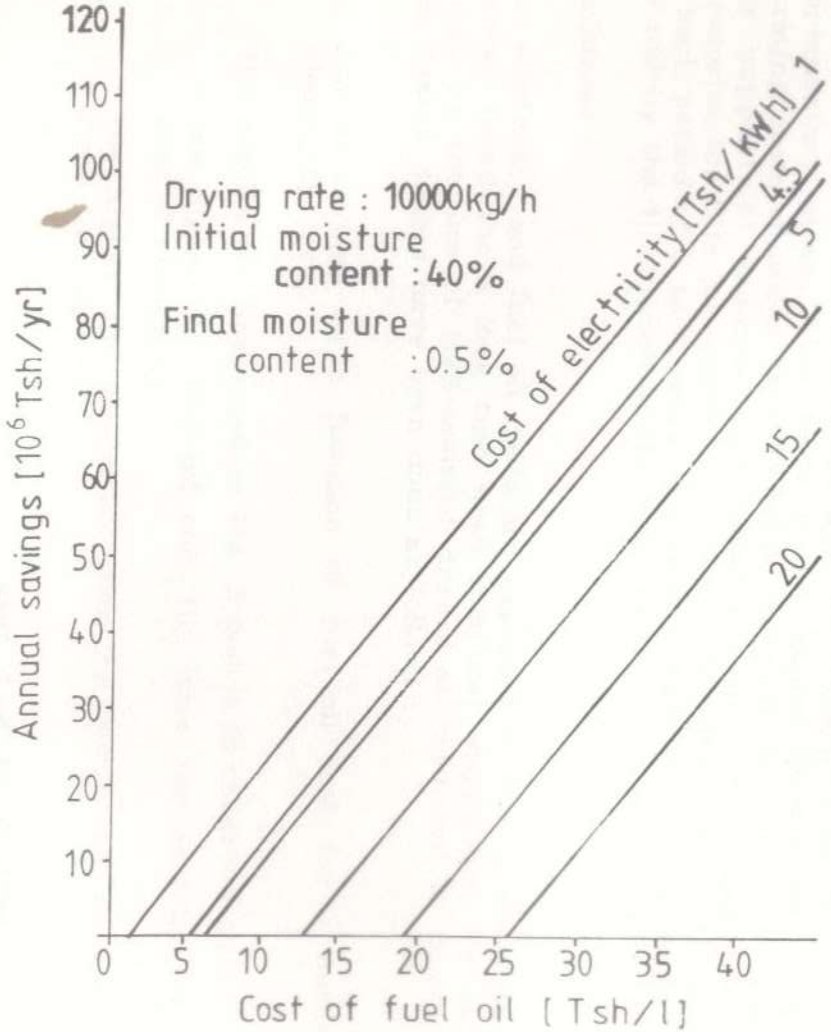

Fig. 5 Annual savings VS cost of fuel Oil - for various initial moisture contents

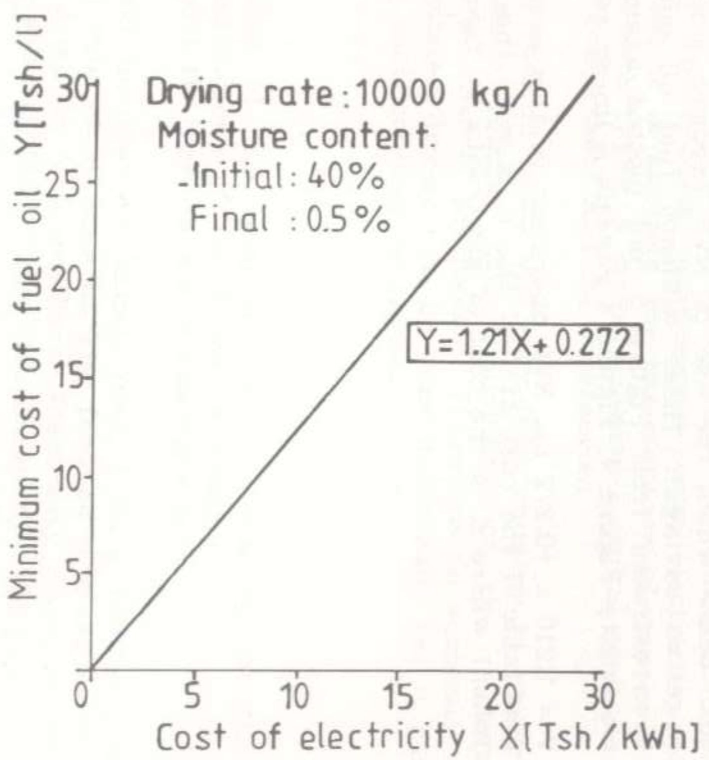

Fig. 6 Comparison of operating costs. conventional steam heated dryer vsMVR-assisted dryer - for various initial moisture content,

(ii) Annual savings plotted in Fig. 5 as a function of fuel oil cost with feed moisture content (reflects evaporation capacity) as a parameter for the present cost of electricity of 4.15 Tshs/kWh. It is observed that higher savings are obtained as more water is evaporated, for example at the present cost of fuel oil of 14.33 Tshsl annual savings rise from $5.5.10^6$ Tshs/year for a 10% wet feed to nearly 30.10^6 Tshs/year for a 50% wet feed.

(iii) The breakdown of operating costs of MVR-assisted drying is given in Fig. 6 as a function of feed moisture content together with the total operating costs of the two types of operation under comparison. It is evident from the graph that electricity forms the major part of the operating cost especially at higher feed moisture contents - it ranges from 54% of the total cost for 20% wet feed to 67% for a 50% of the total cost for a 20% wet feed to 67% for a 50% wet feed. However, due to the high unit price of steam the operating costs of a convetional steam heated dryer remains higher over the whole range of feed moisture contents - varying from 192% to 216% of those of MVR - assisted dryer at 20% and 50% feed moisture contents respectively.

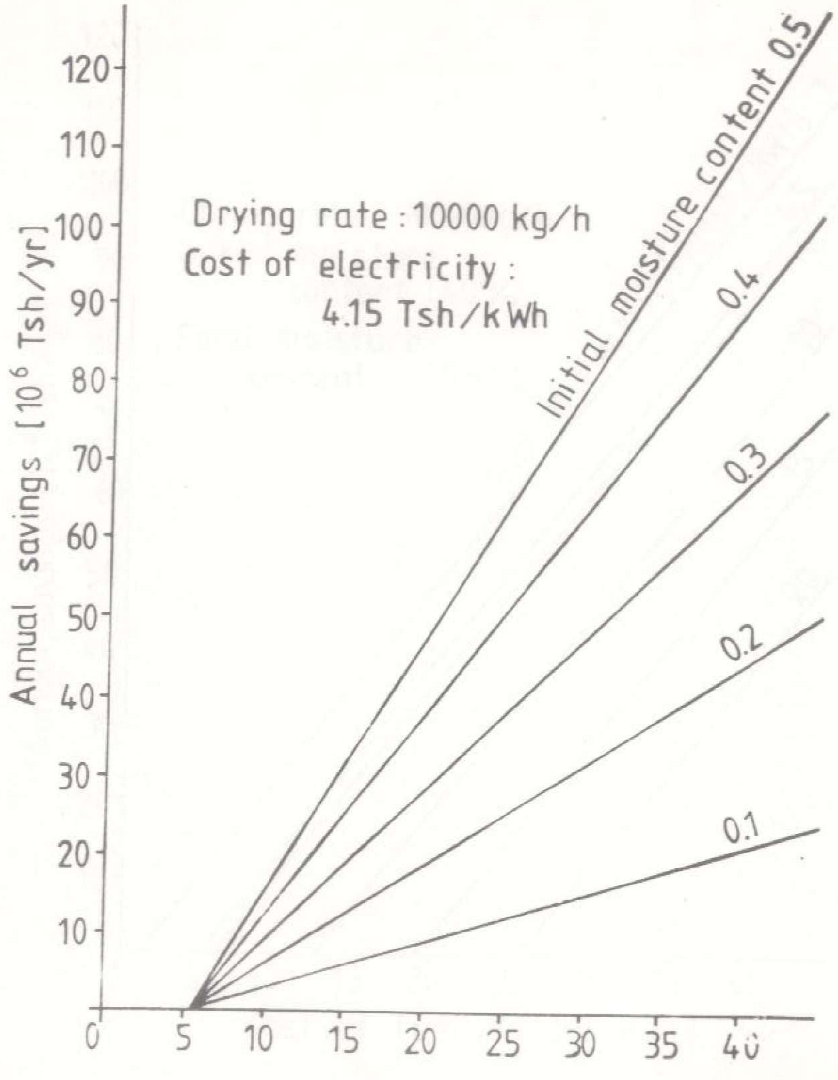

Fig. 3 Annual saving vs cost of fuel oil for various cost of electricity

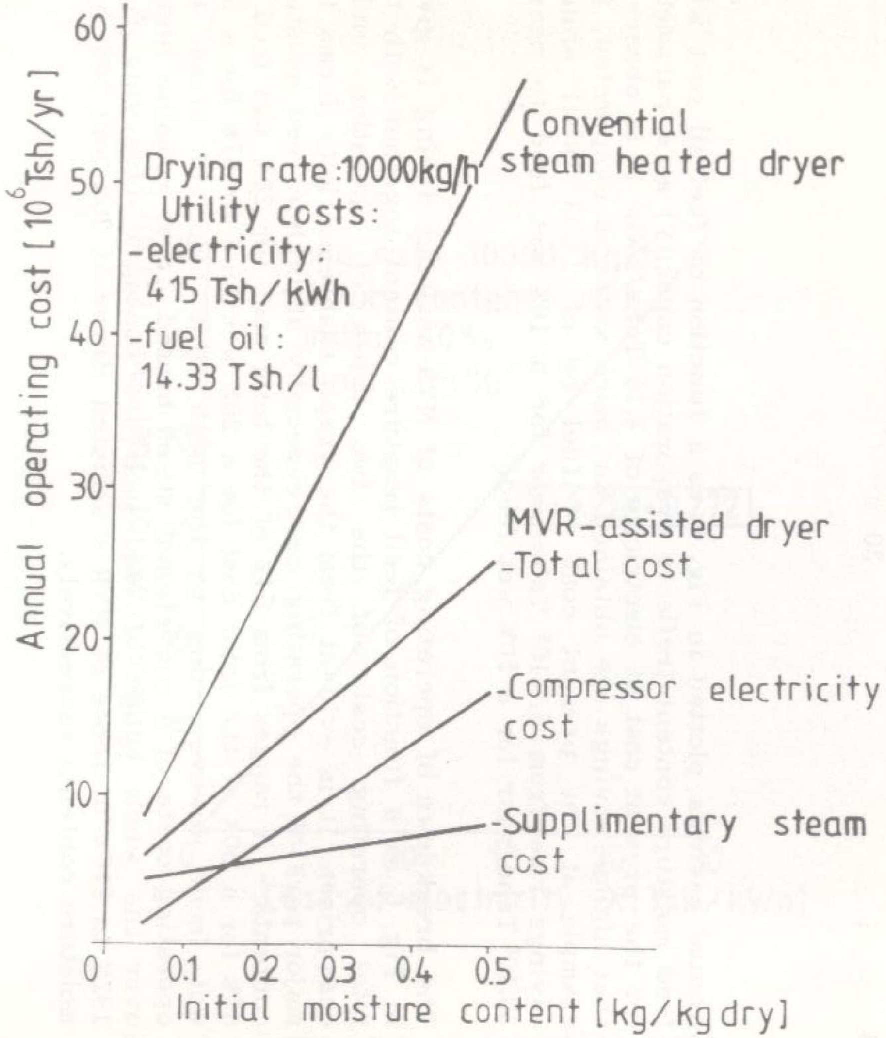

Fig. 4 Minimum cost of fuel oil for profitable operation vs cost of electricity

CONCLUSION

This paper has outlined the methods of conservation of energy in the drying industry to be :

- better care and operation of existing dryers,
- reducing feed moisture contents by less costly means whenever possible,
  and
- recovery of heat from exhaust gases or vapours.

Mechanical VAPOUR RECOMPRESSION has been put forward as a suitable method for recovery of heat from the exhaust water VAPOUR in steam-heated dryers. The twin screw compressor, though a bit costly compared to other machines of same capacity, has been proposed as a suitable component of the MVR package.

In the light of increasing fuel oil cost comparison of operating costs of MVR assisted dryers and the convetional stem heated dryers has indicated that the former should be given serious attention in the drying industry. However, this also depends on the cost of electricity. The application of MVR in industrial drying will therefore be most suitable in countries where electricity is cheaper than fuel oil.

Due to the high capital costs involved the use of MVR is limited to high capacity drying operations such as in paper making, fertilizer, animal feed industry and the like so as to have favorable payback periods. MVR can be included in new designs or retrofitted in existing dryers.

Nomenclature

h	enthalpy, kJ kg^{-1}
S	entropy, kJ kg^{-1} K^{-1}
X	wetness fraction.

Subscripts

f	saturated liquid
g	saturated VAPOUR

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APPENDIX

Comparison of operating costs of a convetional steam heated dryer with those of MVR assisted steam dryer for drying spent grain.

Data

Throughput of spent grain : 10000 kg/h dry.

- Moisture content (kg/kgdry)
- Initial : 40%
- Final : 0.5%

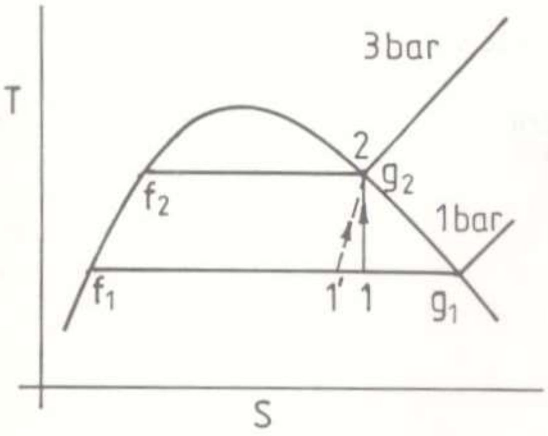
Specific heat of dry spent grain : 1.465 kJ/kgK
Feed temperature : 30^0C
Compressor - inlet pressure : 1 bar abs
- outlet pressure : 3 bar abs
- Isentropic efficiency : 0.75
- Mechanical efficiency : 0.9
- Electrical efficiency : 0.8

Cost of fuel oil : 14.33 Tsh./1
Net calorific values of oil : 41020 kJ/1
Boiler efficiency : 70%
Operational period : 8000 h/annum

Calculation

(i) NVR - Dryer

The VAPOUR compression path on a T - S diagram s as shown on the sketch below:



from steam tables (7)
h_{f2} = 417.5 kJ/kg
h_{g1} = 2675 kJ/kg
h_{g2} = 2724.7 kJ/kg
S_{f1} = 1.3027 kJ/kgK
S_{g1} = 7.3598 kJ/kgK
$S_{g2} = 6.9909 \frac{kJ}{kg}$

1 - 2 : ideal (isentropic) path
1 - 2 : actual path
$h_2 = h_{g2}$ = 2724.7 kJ/kg
$S_1 = S_2$ = S_{g2} = 6.9909 kJ/kgK
But S_1 = $X_1 S_{f1} + (1 - X_1) S_{g1}$

$$X_1 = S_{g1} - \frac{S_1}{S_{g1}} - S_{f1} = \frac{7.3598 - 6.9909}{7.3598 - 1.3027} = 0.0609$$

Also h_1 = $X_1 h_{f1} + (1 - X_1) h_{g1}$
h_1 = 0.0609 x 417.5 + (1 - 0.0609) 2675.4
= 2537.9 kJ/kg

Isentropic work of compression
$= h_2 - h_1 = 186.8$ kJ/kg

Actual work of compression

$$= h_2 - \frac{h_1}{Z} = \frac{h_2 - h_1}{n_{ic}} = \frac{186.8}{0.75} = 249.07\, kJ/kg$$

$h_1 = h_2 - 249.07 = 2475.63$ kJ/kg

Actual wetness fraction at compressor inlet

$$X_1 = \frac{h_{g1} - h_1}{h_{g1} - h_{f1}} = 0.0885$$

To attain this wetness state hot condensate from the dryer heating element is injected at compressor inlet.

Evaporation rate in dryer= 10000 (0.4 - 0.005)
= 3950 kg/h
Condensate injected = 0.0885 x 3950 = 349.6 kg/h

Total flow through compressor = 4299.6 kg/h
Total actual compressor power requirement

$$= \frac{249.07 x 4299.6}{3600} x \frac{1}{0.9} x \frac{1}{0.8} = 413 kW$$

At 4.15 Tshs/kWh, electricity cost
= 1714.61 Tsh./h.

Heat required for evaporation (at 1 bar a)
= (2675.4 - 417.5) X 3950
= 8918705 kJ/h

Heat required for preheating feed to 100°C
= 10000 x (100 - 30) [0.6 x 1.465 + 0.4 x 4.2]
= 1791300 kJ/h

Total heat required = 10710005 kJ/h
Heat available from compressor discharge (on condensing 3 bar a steam)
= (2724.7 - 561.5) x 4299.6
= 9300895 kJ/h

Deficit of heat with MVR (to be obtained from external steam supply)
= 1409110 kJ/h

Cost of oil burned in a boiler to produce this heat

$$\frac{1409110}{41020} x \frac{1}{0.7} x 14.33 = 703.23 Tsh./h$$