Recovery of energy from the water going down mine shafts

by A. WHILLIER*, Pr. Eng., Sc. D. (M.I.T.) (Fellow)

SYNOPSIS

The influence of energy-recovery systems on the rise in temperature of water going down mines is examined. It is concluded that the cost benefit of such systems, deriving partially from the reduced temperature rise in situations where cold water is sent underground from surface, would more than justify the installation cost.

SAMEVATTING

Die invloed van energieherwinningstelsels op die temperatuurstyging van water wat in die myne afgaan, word ondersoek. Die gevolgtrekking wat gemaak word, is dat die kostevoordeel van sulke stelsels, deels op grond van die kleiner temperatuurstygings op plekke waar koue water van die oppervlak af ondergronds gestuur word, die installeringskoste heeltemal sal regverdig.

Introduction

A consequence of the use of mine service water for the distribution of coolness to the stoping areas of deep mines is that in many instances some of the refrigeration plant can be located beneficially on the surface. Two drawbacks of surface-located refrigeration plant are the high cost in pumping the service water back to surface, and the rise in temperature of the water (by $g/Cp=9{,}79/4{,}19=2\frac{1}{3}$ °C per km of depth) resulting from the dissipation by friction of the potential energy of the water into thermal energy.

It has been suggested that some of the potential energy of the downgoing water could be recovered in a simple water turbine, so as to at least halve the net pumping power demand. Such an arrangement would have the added advantage of halving the increase in temperature of the water, giving a substantial increase in cooling available in the stopes.

The additional cost involved in an energy-recovery system arises from the need for a high-pressure pipe with a larger diameter in place of the conventional small low-pressure pipe for the downgoing water. This is in addition to the cost of the turbine itself.

This paper gives an outline of the influence of such energy-recovery systems on the temperature rise of the water, and of the cost benefits arising from their use. The nomenclature is given at the end of the paper.

Mollier Diagram for Water

A portion of a Mollier diagram for water, in which the energy content (enthalpy) is plotted against entropy, is shown in Fig. 1. In this diagram, three lines of constant pressure are shown rising up towards the right, and being intersected by almost vertical lines of constant temperature. The three isobars correspond to water at ambient pressure, 1000 m deep and 2000 m deep respectively. The isobars are almost straight, having a slope equal to T, the absolute temperature. The vertical distance separating these lines is about 9,8 kJ/kg. The entropy is not given since it is not required in any of the calculations.

*Environmental Engineering Laboratory, Chamber of Mines of South Africa, Johannesburg.

The isotherms on such a Mollier diagram are vertical at temperatures between 3 and 4 °C (where water has its maximum density) but slope increasingly to the left at higher temperatures. At 15 °C, the deviation from true vertical is about 0,1 °C over a depth of 1000 m. For the purposes of this report, these small deviations of the isotherms from the vertical will be neglected. (The effect becomes significant only when it is desired to deduce the efficiency of water pumps or turbines from measurements of the change in temperature across such devices.)

In order to illustrate the use of the Mollier diagram, an example will be considered in which water at 10 °C is assumed to flow down a pipe to a depth of 1000 m. This water on entering the pipe would be represented by the point a in Fig. 1.

Heat transfer between the water and its surroundings will be neglected, since the effect of such heat transfer on the temperature of the water would be additive, and therefore corrections for any assumed rate of heat transfer can be made later if needed.

Ideal Frictionless Flow

If the flow of water down the pipe were frictionless (or if there were no flow), the pressure increase, Δp, corresponding to a change in depth Δz would be

$$\Delta p=\rho\, g\, \Delta z. \qquad (1)$$

The average density of the water in the pipe would be about 1001 kg/m³, and, with the value of g for South Africa taken as 9,79 m/s², the increase in pressure corresponding to a depth of 1000 m is about 9,8 MPa (98 bar or 1421 lb/in²). The absolute pressure of the water at the bottom of the pipe would hence be 9,8+0,1=9,9 MPa (99 bar).

Since in this case the flow is assumed to be frictionless and adiabatic (no exchange of heat with the surroundings), the process would be isentropic, and therefore would follow a vertical line in Fig. 1 from point a to point f. The temperature of the water at point f is practically identical to the temperature at point a.

The increase in energy content of the water for this process would be

$$\Delta h=h_f-h_a=g\,\Delta z=\bar{v}\,\Delta p, \text{ i.e.} \qquad (2)$$

Δh=9,79 kJ/kg per 1000 m depth.

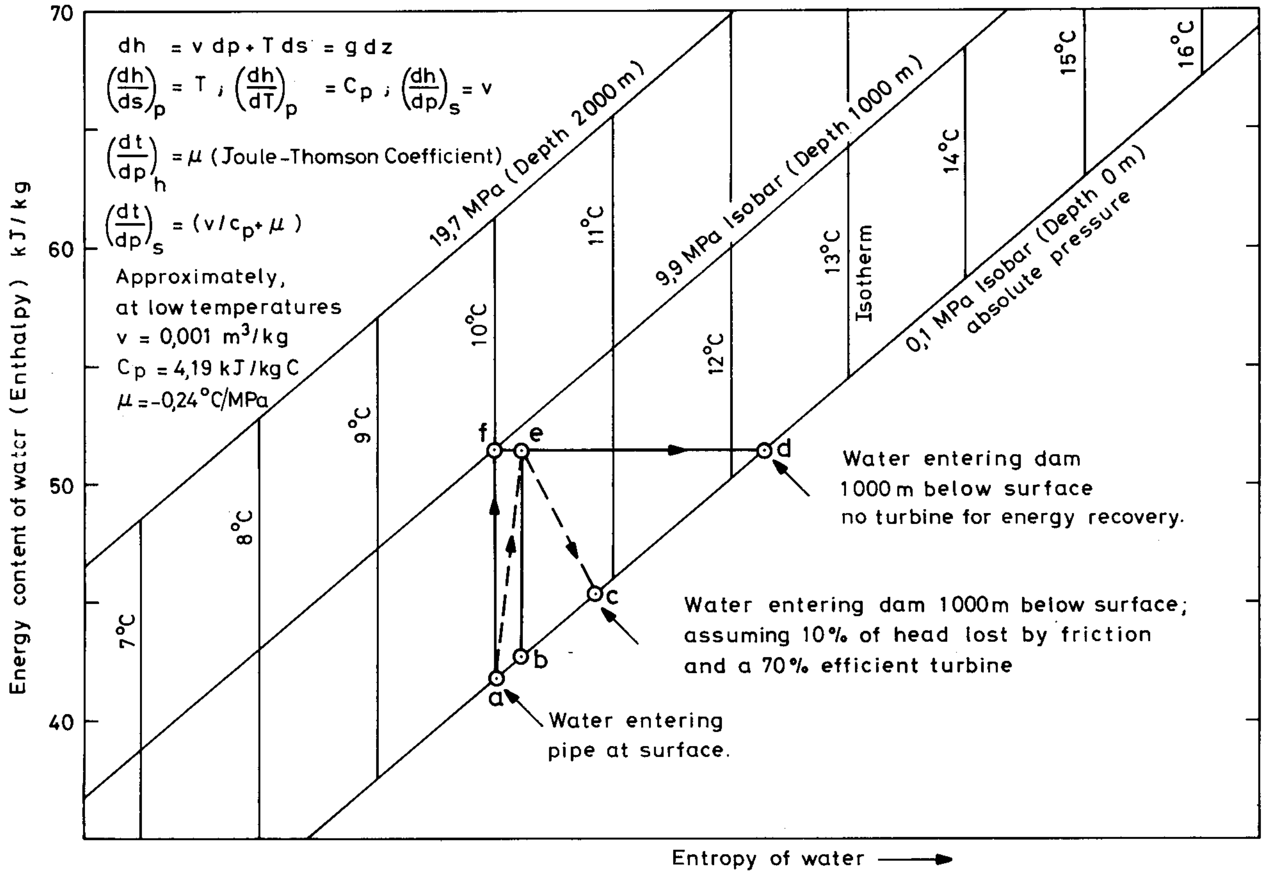

Fig. 1—Mollier diagram for water

Frictional Flow

If the water at high pressure in the bottom of the pipe were permitted to escape through a valve into a dam, the high pressure would create a very high velocity through the valve, which in turn would be dissipated in the dam by turbulence and friction. This frictional dissipation process from high pressure to low pressure (often referred to as expansion, particularly where gases are involved) is a process of constant energy content of the water, or constant enthalpy, represented by a horizontal line in Fig. 1 from *f* to *d*.

At point *d* the water is again at ambient pressure, which is assumed to be 100 kPa (1 bar or 0,1 MPa). It will be seen that the temperature of the water has now increased by 2,33 °C in going from point *f* to point *d*. This increase in temperature can be calculated by considering the isobar from *a* to *d*, since, *for constant pressure*, the enthalpy and temperature are related by the specific heat at constant pressure, *Cp*, as follows

$(\Delta h)_p = Cp\ \Delta t$ . . . . (3)

The increase in enthalpy between *a* and *d* is the same as the increase between *a* and *f*, namely 9,79 kJ/kg, so that the rise in temperature from *a* to *d*, if the specific heat of water at this temperature is assumed to be 4,19 kJ/kg C, is

9,79/4,19=2,33 °C.

If it is recollected that this calculation is for a depth of 1000 m, it will be seen that the rise in temperature of water flowing down a vertical pipeline and ending at ambient pressure in a dam at the bottom is 2,33 °C per kilometre of depth.

It is irrelevant whether the frictional dissipation takes place continuously down the pipeline, which would occur if the pipeline were operated at terminal velocity, or whether the dissipation occurs entirely at the exit end of the pipeline as was assumed above.

Recovery of Energy

When energy is to be recovered from the water going down a shaft, the pipeline must be sized so as to keep the velocity of the water at about 3 m/s if the friction losses are to be kept reasonably small. If, for example, the friction losses are 10 per cent of the total head, the pressure of the water reaching the bottom of the pipe would be equivalent to a head of 900 m and the temperature would have increased by 0,233 °C. This condition is represented by point *e* in Fig. 1.

If this water were passed through a perfect turbine, the water would return to ambient pressure along a line of constant entropy ending up at point *b* in Fig. 1. If, on the other hand, a turbine of say 70 per cent efficiency were used, the final condition of the water would be as represented by point *c* in Fig. 1.

The turbine efficiency, η_T, is defined as

$\eta_T = (h_e - h_c)/(h_e - h_b)$. . . . . (4)

The temperature of the water leaving the turbine at a condition corresponding to point *c* can be read off Fig. 1,

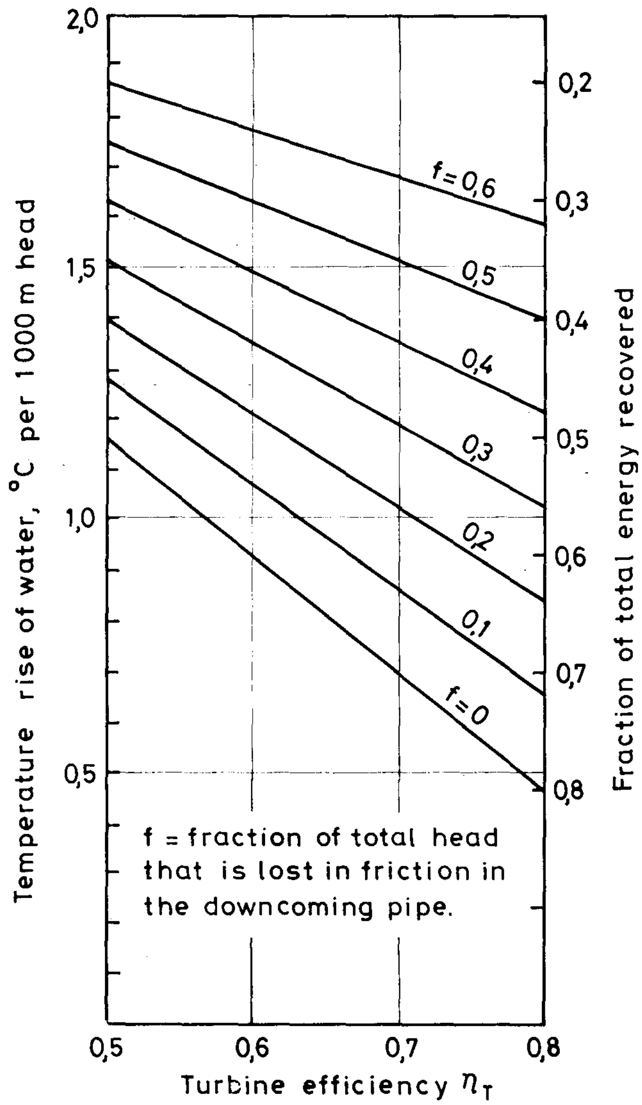

Fig. 2—Influence of energy recovery on temperature rise of the water

or it can be calculated from equation (5):

$(t_c-t_a)=[f+(1-\eta_T)(1-f)]\,[0{,}00233\,H]$, ... (5)

where η_T = efficiency of the turbine,

f = fraction of the total head that is lost in friction,

H = total head in metres, and

$g/Cp=0{,}00233$ °C/m.

For the above example with $\eta_T=0{,}7$, $f=0{,}1$, and $H=1000$ m, equation (5) gives the temperature rise as 0,862 °C, which is only 37 per cent of the original rise of 2,33 °C.

In order to facilitate calculations, equation (5) has been plotted in Fig. 2 for various assumed values of f and η_T. The left-hand scale in Fig. 2 indicates the actual rise in temperature of the water per 1000 metres of depth, while the right-hand scale indicates the fraction of the total energy that is recovered for different combinations of f and η_T.

Additional Cooling in Stopes

In addition to the saving in the net power costs for pumping, an energy-recovery system has a benefit in making more cooling available in the stopes. This can be illustrated by consideration of a case where the water goes down 2000 m before reaching the stoping horizon of a mine. The temperature of the water would increase by $2\times2{,}33=4{,}66$ °C if no energy-recovery system were used, but by only 1,73 °C on the assumption of a pressure-recovery system with $f=0{,}1$ and $\eta_T=0{,}7$. The difference $(4{,}66-1{,}73)=2{,}93$ °C represents additional cooling that would be available for the stopes. Thus, if the water is sent down the shaft at 10 °C and is pumped out of the mine at 30 °C, the increase in cooling is (2,93)/(30—14,66) or 19 per cent. On the other hand, if the water were sent down the mine from the surface at 0 °C, the additional cooling would amount to (2,93)/(30—4,66) or 11,6 per cent. Both represent a very considerable increase in the cooling that would be available at the stopes.

Cost Benefit

In order to illustrate the cost benefit of a pressure-recovery system, an example will be considered with the following assumptions.

Effective depth to stoping horizon	2000 m
Water flow-rate down shaft (24-hour average)	100 l/s
Fraction of energy recovered	0,6
Annual cost of 1 kW (electric)	R60
Annual value of 1 kW of cooling	R100

Theoretical power $= m\ g\ H = 100$ l/s $\times 9{,}79\times2000/1000$ $=1958$ kW

Rate of recovery of energy $=0{,}6\times1958=1170$ kW

Value of energy recovered, at R60 p.a. per kW is $1170\times60=$ R70 488 p.a.

From Fig. 2, the rise in temperature of the water with 60 per cent recovery of energy is 0,93 °C per kilometre or 1,86 °C for a depth of 2 km.

Temperature-rise without energy recovery $=2\times2{,}33=4{,}66$ °C.

Additional cooling in stopes resulting from the lower temperature of the water is

100 l/s $\times4{,}19\times(4{,}66-1{,}86)=1170$ kW.

Annual value of the extra cooling = R117 000 p.a.

The total annual cost benefit of energy recovery (at 60 per cent efficiency) is as follows:

R70 488 + R117 000 = ≈ R187 000 p.a.

Note At a 50 per cent recovery of energy, the cost benefit would be R58 740 + R97 394 = ≈ R156 000.

These annual cost benefits would justify an expenditure of about R500 000 on the energy-recovery system, which is far in excess of the actual cost of such systems.

Conclusion

The examples given in this report suggest that the investment in energy-recovery systems in shafts where cold service water is sent underground from surface would be well justified.

Nomenclature

Cp Specific heat of water at constant pressure, 4,19 kJ/kg °C

f Fraction of head dissipated in friction

g Local gravitational acceleration, 9,79 m/s^2
H Vertical depth of pipe, m
h Enthalpy (energy content) of water, kJ/kg
p Pressure, Pa or MPa
t Temperature, °C
$\bar{v}$ Average specific volume of water, m^3/kg
z Vertical distance, m
η_T Efficiency of energy-recovery turbine
ρ Average density of water in the pipe, kg/m^3

Acknowledgement

This report arises from work carried out as part of the research programme of the Research Organisation of the Chamber of Mines of South Africa.