Latent Power Turbine: Proof-of-concept experiments

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Abstract - The Latent Power Turbine concept describes a novel type of turbo-machine that harnesses latent heat in the exhaust steam from conventional electricity generation stations, usually dissipated into the environment

The experiments at Lancaster University during 2010 show that a Latent Power Turbine (LPT) can offer the possibility for additional electricity generation, with no increase in consumption of fossil, nuclear, or biomass fuel. The concept aims to capture latent heat by encouraging condensation, as exhaust steam from the primary power cycle passes through each LPT stage. To ensure condensation, the steam velocity is sub-sonic, and the operating temperatures remain low throughout the LPT process. In the proof of concept experiments, the turbine delivered measurable power outputs when the water vapour condensed inside the turbine at temperatures of about 20^{o}C.

These experiments were carried out using small-scale apparatus, where viscous drag and other forms of friction almost swamped the results. Nevertheless, sufficient evidence was gathered to suggest that larger LP Turbines have the potential for converting the latent heat stored in low temperature saturated steam into useful shaft power.

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1. Introduction

1.1 The carbon abatement problem to be solved

Steam turbines are the workhorses of the electricity supply industry. They are the most cost effective devices for converting the energy stored in coal, nuclear fuel, gas, geothermal heat and biomass into electricity: 86% of the World's electricity is produced using steam turbines. Steam turbine efficiency increases with boiler temperature and pressure. The most efficient units are found in coal and nuclear powered stations. They run at the extreme temperature and strength limits of modern materials, but can only deliver between 40% and 48% efficiency, depending on the detailed plant design and the relative sophistication of the heat transfer process.

The reason for this disappointing performance is that a large amount of latent heat energy must be provided to convert boiling water, the working fluid used to power the turbines, into steam at the boiling temperature. Conventional "Rankine cycle" thinking on steam turbine design is that the latent heat is trapped inside the steam, and can only be released as waste heat at the end of the turbine cycle. This thinking has guided electricity generation plant design for more than 100 years, tacitly accepting that one half of the input energy at all of the many generating plants around the world has been dissipated by exhausting to the environment. It is worth noting that nature is far more efficient: tropical hurricanes are driven by heat engines fuelled by the latent heat of condensation, released as rain droplets form at about 26.5°C. This fact was the starting point for development of the Latent Power Turbine theory, which has now been demonstrated to be a potentially viable technology.

The diagram below summarises the problem.

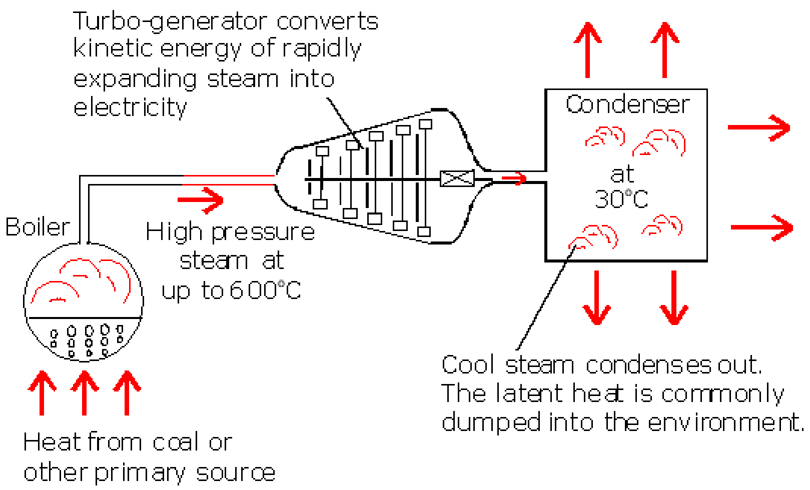


Figure 1. The waste heat can be used for district heating, but not many people are keen on living close to large power stations.

1.2 The proposed solution

Instead of feeding saturated steam exhaust from the main generator turbines into a condenser unit or to cooling towers, it is proposed to pass the steam through a chain of turbine chambers, gradually decreasing in volume, so that the steam remains saturated. Turbo-machines of this type are referred to as Latent Power Turbines.

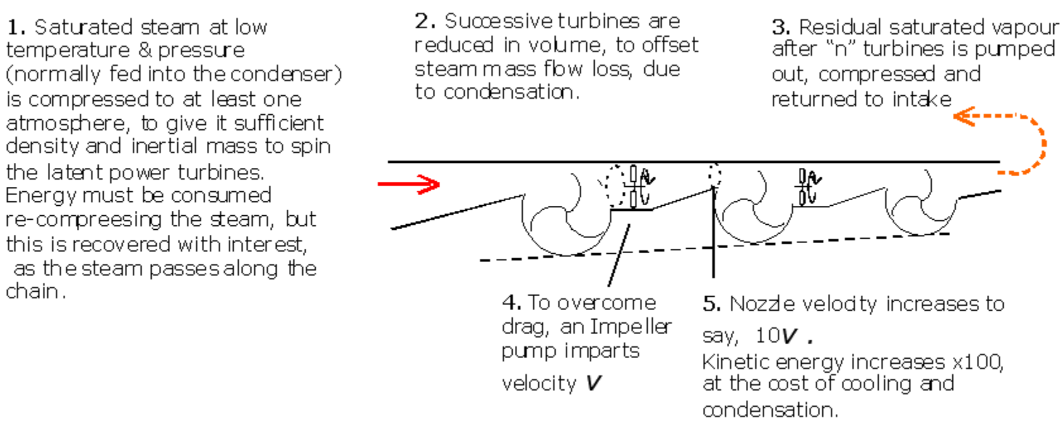


Figure 2. Part of a chain of latent power turbines.

As a precursor to the experimental work described in this report, during 2006 a group of Lancaster University students carried out a series of iterative calculations, to predict the number of stages required to extract a significant fraction of the residual latent heat from power station exhaust steam. The nozzle velocity was kept sub-sonic, in order to prevent irreversible steam expansion, and the outputs for these calculations are shown in Figure 3 below:

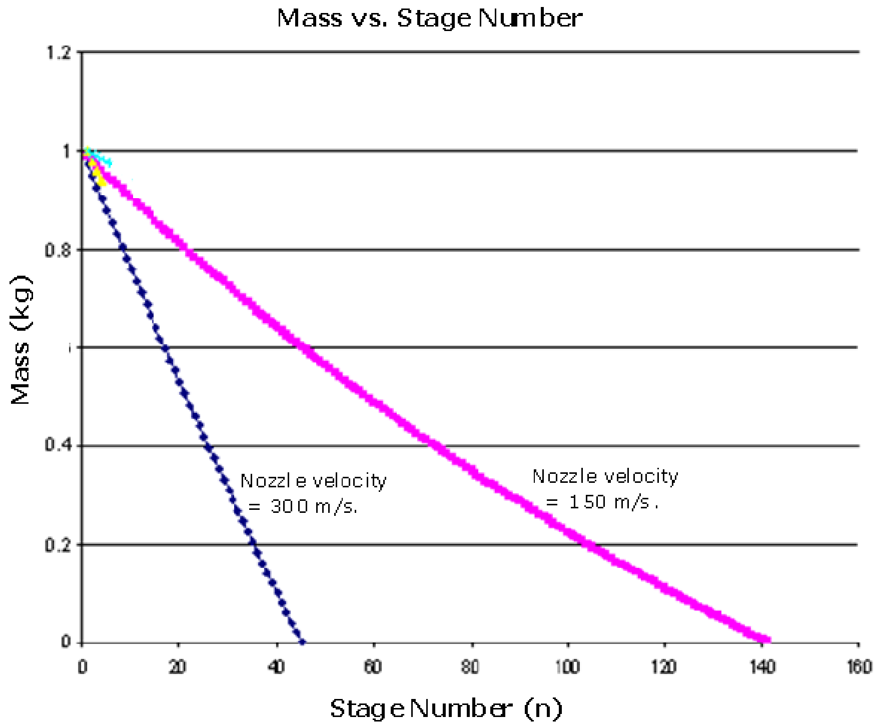


Figure 3. Calculating the number of Turbo-machine stages required to absorb the latent heat energy in exhaust steam from a power generation turbine.

This calculation suggested that a key element in Latent Power Turbine design will be the pressure drop per stage that can be achieved in practice. The pressure drop directly affects the stage power output, and also the amount of partial condensation of the input steam – hence the heat energy released from the latent heat of condensation.

The theoretical model used by the students to generate Figure 3 is explained in Appendix 3.

2. The literature search for similar inventions

The Lancaster University research database search encompassed academic journal and conference papers as far back as the early years of the last century. No work into the deliberate provocation of condensation inside steam turbines, with the intention of increasing efficiency, appears to have been done. These negative findings are confirmed by three patent literature searches carried out by the UK Intellectual Property Office, in response to patent applications filed by the present inventor, Courtney. [1, 2, 3.]

Prior to the Second World War, research was done into condensation inside turbines, but with the view to eliminating it as a nuisance. In 1937 Binnie et. al. [4, 5] investigated the steam pressure drop in convergent-divergent nozzles. They noted that under certain circumstances condensation occurred close to the throat of the constriction, with the release of latent heat and a sharp increase in pressure.

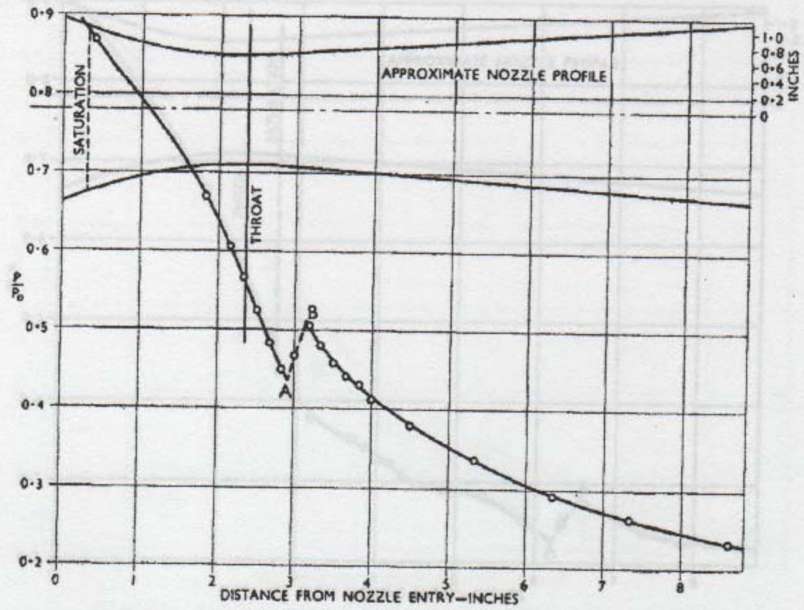


Fig. 10. Axial Pressure Distribution (Test No. 49)
P_o, 20·88 lb. per sq. in. abs.; T_o, 245·7 deg. F.

Figure 4. This graph from Binnie [4] shows an increase in pressure, as a result of condensation. A second paper by Binnie [5] describes an elegant electrode method for determining the onset of saturation.

Binnie wrote, "In the authors' experiments a sharp rise in pressure from the point where condensation commenced was invariably observed, as had been predicted by Keenan." [Reference 4, page 248.]

The pressure spike is in line with our own theory. It also supports our prediction that a correction term will be required for Bernoulli's equation when a phase change takes place inside a Venturi throat.
Here is our argument: The LPT working fluid is compressible; nevertheless, changes in pressure can be estimated with a fair degree of accuracy using Bernoulli's equation. This states that for an incompressible, non-viscous fluid undergoing steady flow, the pressure **(p)** plus the kinetic energy per unit volume (**1/2**x density,ρ x velocity, **v** squared) plus the potential energy per unit volume (density ,ρ x acceleration due to gravity, **g** x height **h**) is constant at all points on a streamline.
Thus,

$$\mathbf{p + 1/2\rho v^2 + \rho g h = A\ constant}$$

If the working fluid includes a saturated vapour, then we predict that Bernoulli's equation breaks down when flowing through a nozzle or Venturi similar to that depicted in Figure 8 below. Any tendency to cool on passing through the Venturi throat will result in the production of small condensation droplets and the release of latent heat. Consequently, the temperature and pressure drops will be reduced compared with the flow of dry fluid. On passing through the flared section, the latent heat processes are reversed, with heat being absorbed as the water droplets evaporate. The rate of mass flow remains constant through all sections of the conduit perpendicular to the streamlines. In the case of a saturated vapour, the rate of volume flow drops as a consequence of condensation in the nozzle, then increases as a consequence of evaporation in the flared section. For the process to be reversible, the condensation droplets must continue to move forward as an aerosol and not come to rest as pools of liquid inside the conduit.

In order to produce an equation that allows for the release of latent heat an additional term dQ_l /dV needs to be added. The term dQ_L /dV represents the latent heat lost/gained per unit volume of static fluid. Thus the generalised form of Bernoulli's equation is

$$\mathbf{p + 1/2\rho v^2 + \rho g h - \boldsymbol{k} dQ_L / dV = A\ constant}$$

Where ***k*** is a dimensionless constant.
Volume is used as part of the correction term, to ensure dimensional consistency.
When condensation occurs and latent heat is liberated, the minus sign is retained in front of the latent heat term. A positive sign is used if evaporation occurs and latent heat is absorbed.

The literature search did not reveal any references to a Bernoulli equation correction term for latent heat, but discovered several references to a correction term for sensible heat changes, for example, Segletes and Walters [6]. We corresponded with the authors of this paper, who considered our arguments to be valid. They went further, by offering suggestions on how our correction was consistent with Van der Waals equation relating to inter-molecular forces.

Latent Power Turbines are designed to maximise the release of latent heat inside the turbine, but this is not always desirable. For example, Roumeliotis and Mathioudakis [7] have reported on the problems caused by the release of latent heat inside aircraft air-conditioning turbines, when air enters the turbine under saturation conditions. The turbines strip out part of the water vapour, but the thermal rejuvenation caused by the release of latent heat means that the exit temperature of the air is too warm for personal comfort. What Roumeliotis and Mathioudakis saw as a nuisance, we now recognise as a merit. We corresponded with Roumeliotis and Mathioudakis, who expressed interest in participating in any future European Latent Power Turbine project.

3. The proof of concept experiments

3.1 Experimental method and equipment

Axial flow turbines as depicted in Figure 2 allow large volume flow rates and are preferred when working with low flow velocities and pressure differentials.

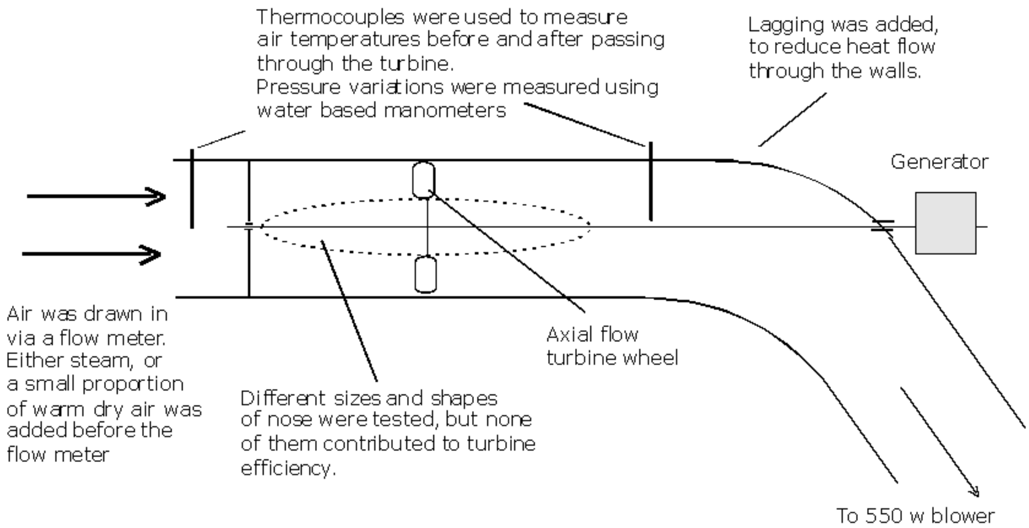


Figure 5. The axial flow experimental rig

The commercial unit is expected to operate with pure steam. However, we elected to investigate air plus steam mixtures for the following reasons:

(i) The system had a low power output, so it was only necessary for a small fraction of the water vapour to condense out. Preliminary calculations suggested that there was sufficient water vapour in saturated air at about 18 ^{o}C to meet our experimental needs.

(ii) It simplified the experimental design because the system could run cooler. This reduced heat loss errors and the safety hazards associated with steam experiments.

Note: Atmospheric air (which naturally includes some water vapour, but is unsaturated) is referred to as "**Dry air**". Air which includes just sufficient added steam to produce a trace of condensation inside the glass wall of the flow meter is referred to as "**Dew point air**".

The experimental rig at Lancaster is shown below:

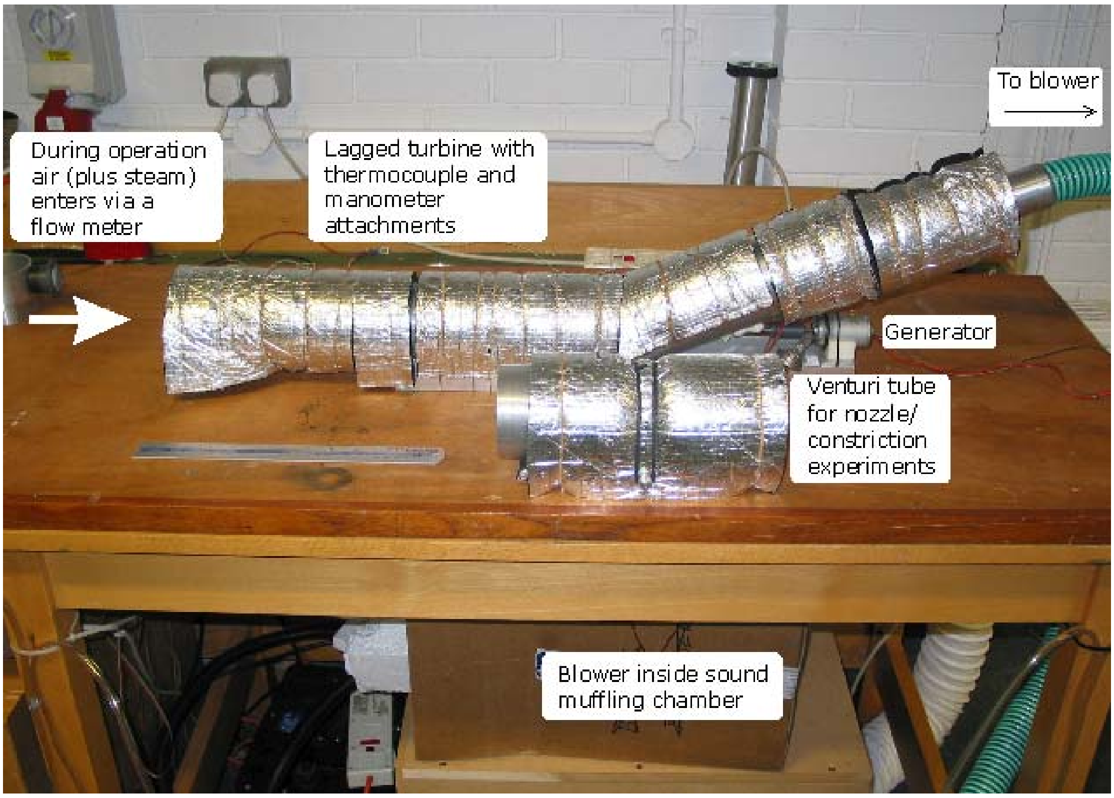


Figure 6. The Lancaster University rig.

3.2 The experiments

Experiment 1.
Before extracting energy from the turbine, the differences in behaviour of dry and dew point air were explored as it accelerated, then decelerated, on passing through a constriction.

It was predicted that,

(i) Provided drag was negligible, both types of air would cool on passing through the throat of a constriction, but the cooling for dew point air would be less, due to the liberation of latent heat.

(ii) Bernoulli's equation would require a correction term when dew point air passed through the constriction.

In reality, due to the small scale of the system, drag played an important role in modifying the airflow. Consequently, these predictions could not be tested but, crucially, dry and dew point air exhibited significantly different behaviours when passing through a constriction. These differences were in line with expectations, supporting the underlying LP Turbine theory.

Experiment 2.
Dry, then dew point air was passed through the turbine, to test for differences in behaviour. Drag still played a dominant role, but, nevertheless, the outcomes were in line with LP Turbine theory.

3.3 Detailed discussion of experiment 1

The purpose of this experiment was to check for differences in behaviour of dry and dew point air as the air moved through the turbine, but without the complications of kinetic energy, and sensible or latent heat being converted into electricity.

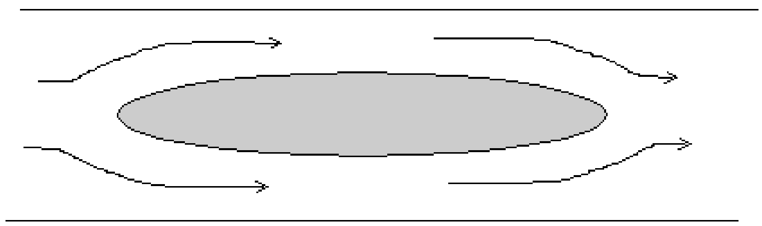


Figure 7. Our aim was to investigate the differences in the behaviour of dry and dew point air as it accelerated, then decelerated, on passing through a constriction.

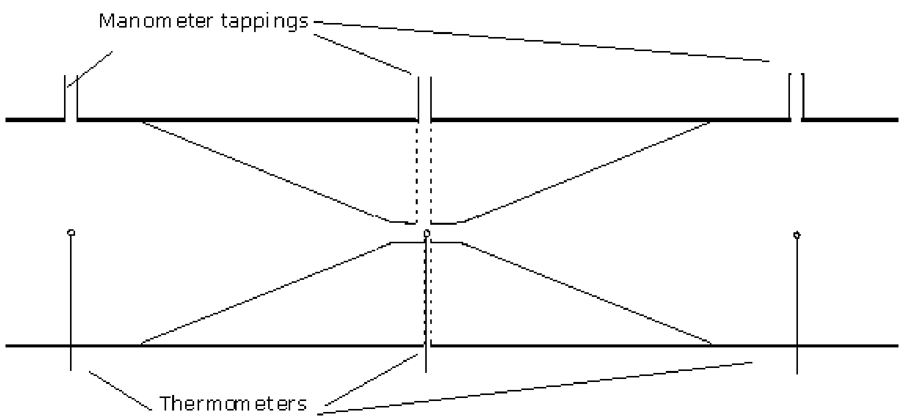


Figure 8. We chose to simplify the experimental design by investigating an equivalent Venturi constriction.

Experiment 1.1 The drag investigation.

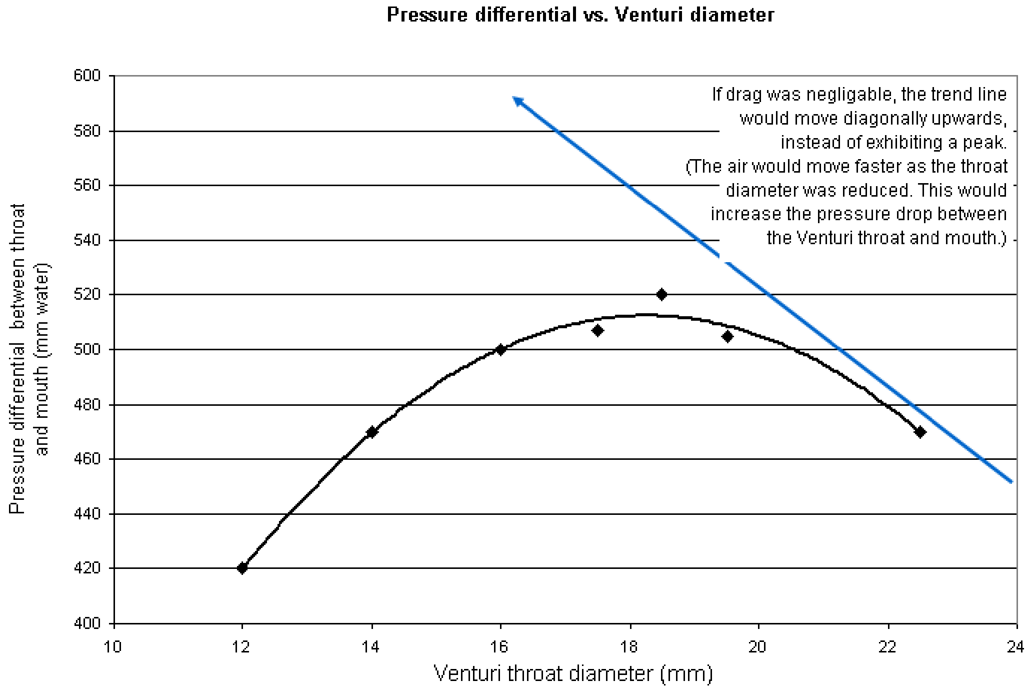


Figure 9. For this experiment, the Venturi constriction was made from polyurethane foam. The pressure drop between the mouth and throat was measured in a series of experiments, in which the throat was gradually widened from 12 mm to 22.5 mm.

Conclusions

(i) The results provided evidence that we were experimenting in a region where drag was starting to swamp the phenomenon we had chosen to investigate.

(ii) As a consequence, we would have to modify our predictions on how the air behaved on passing through a constriction.

(iii) It suggested that the optimum throat diameter for a more in-depth experiment was 18.5 mm.

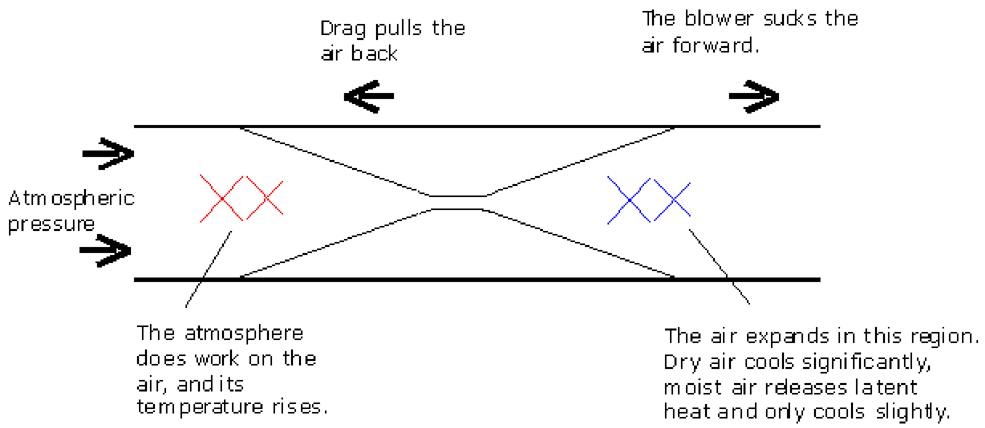


Figure 10. These were our modified predictions on how the constriction system would behave under significant drag conditions.

Experiment 1.2 Testing the modified predictions.

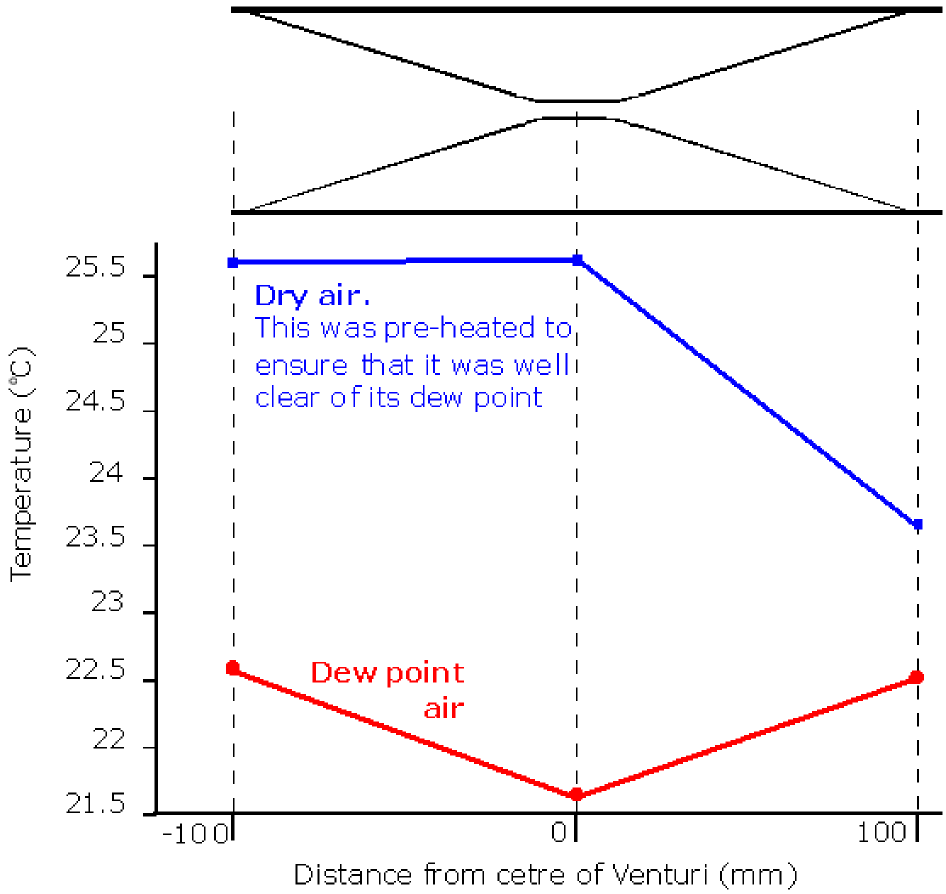


Figure 11. The test results demonstrate that the presence of saturated water vapour significantly modifies the behaviour of air as it passes through a constriction or nozzle.

3.4 Detailed discussion of experiment 2

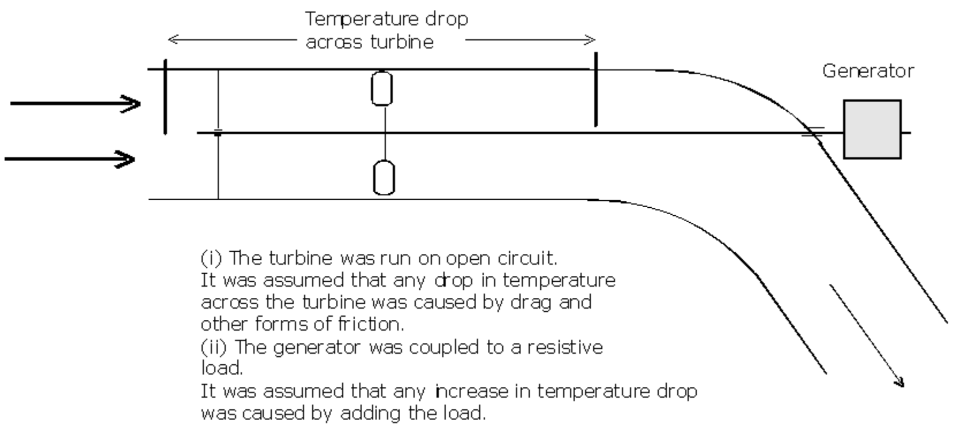


Figure 12. For both dry and dew point air experiments, the turbine was first run on open circuit, then, the load added.

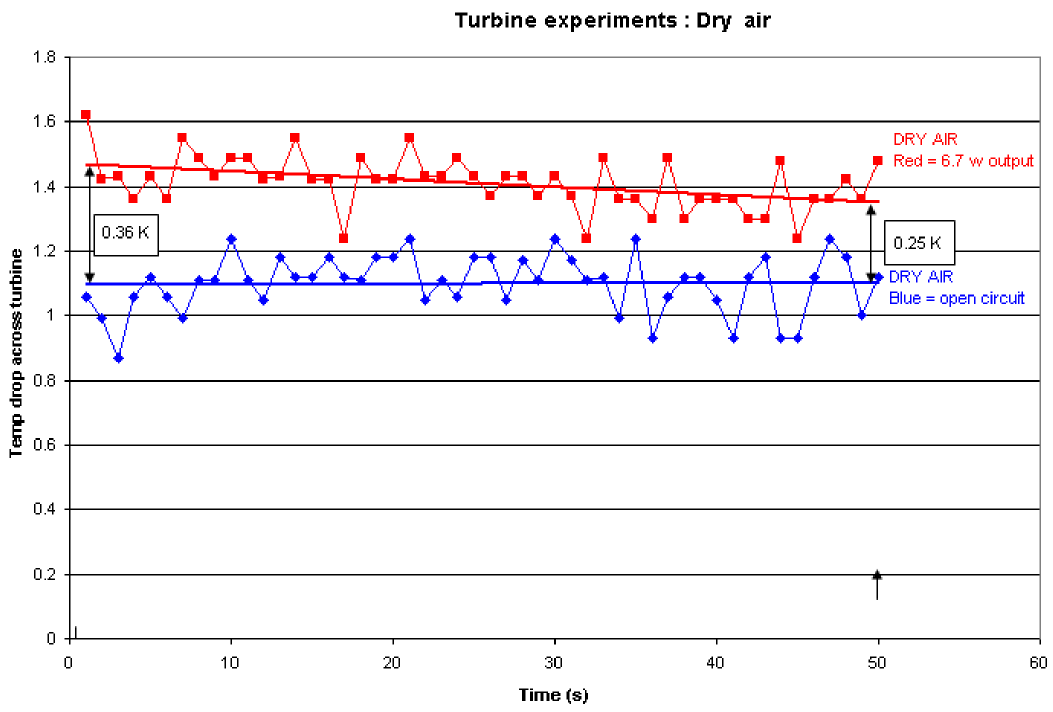


Figure 13, Dry air experiment. The temperature drop across the turbine increases by about 0.3 K when the resistive load is added.

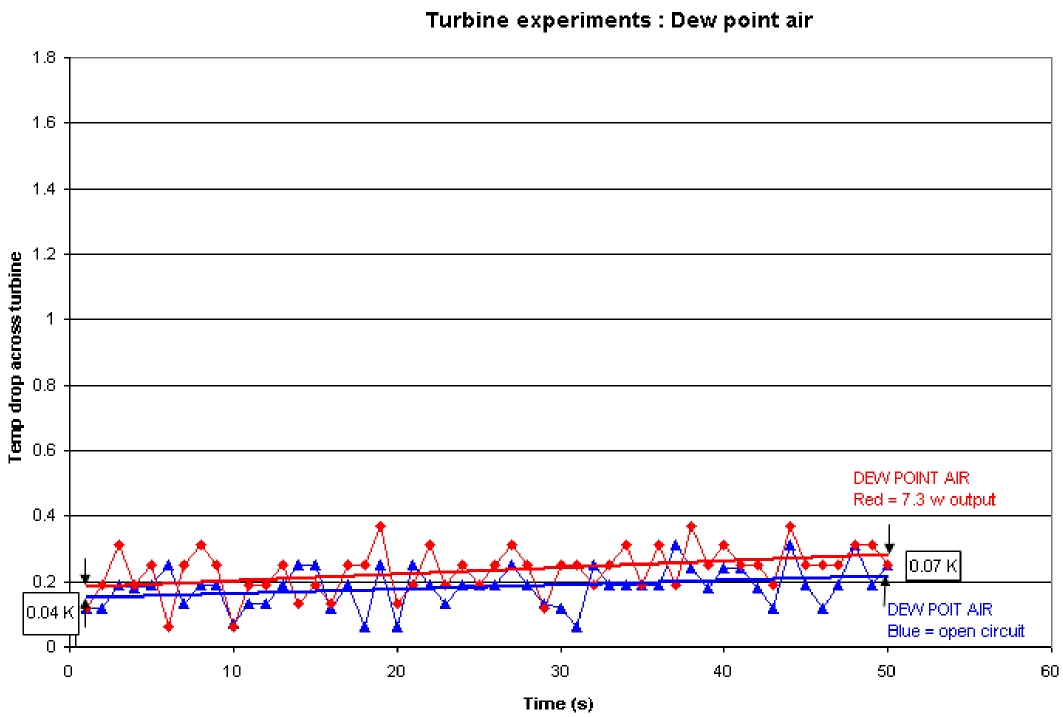


Figure 14, Dew point air experiment. The temperature drop across the turbine increases by about 0.06 K when the resistive load is added.

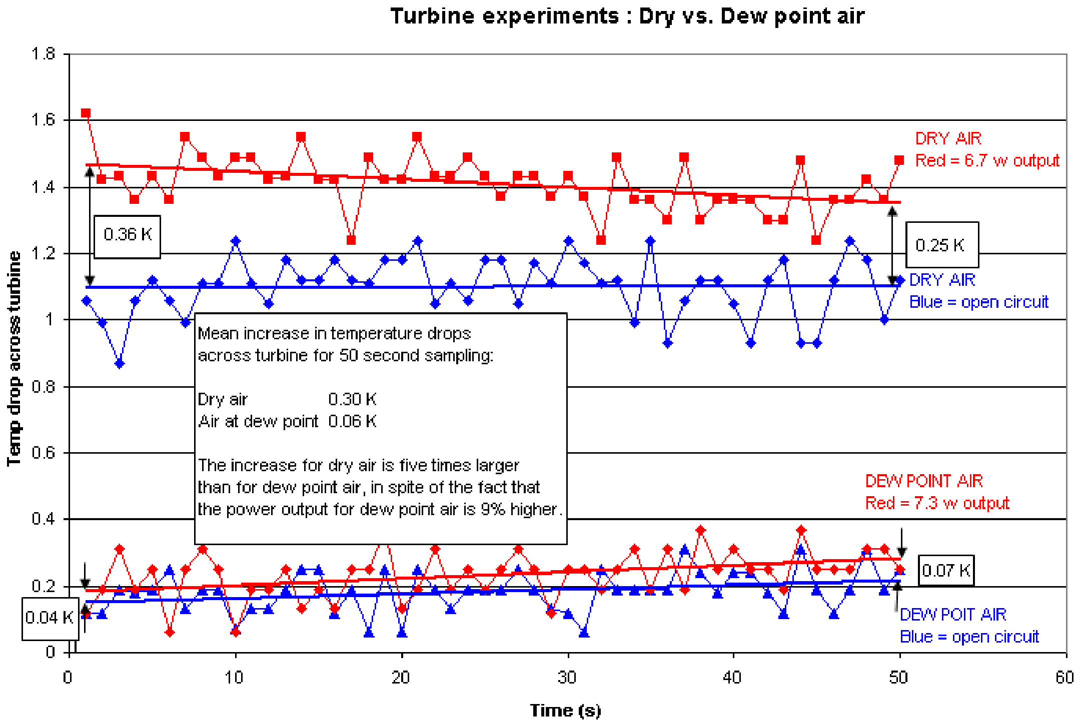


Figure 15, Combined results from dry and dew point air experiments.

4 Comparison of the behaviour of an LP Turbine with a Carnot engine

Dry air

Temp before turbine	Temp after turbine	Power output (w)	Measured efficiency (550 w blower)	Maximum efficiency predicted by Carnot equation Efficiency= 1-(T_c/T_H)	Comment
25.16 °C = 298.16 K	23.70 °C = 296.70 K	6.73	**1.22%**	**0.45%**	The extra efficiency appears at the cost of losing kinetic energy.

The turbine superficially appears to be more efficient than a Carnot engine. *But this is only an illusion*, because the parallel sided turbine system is not a pure heat engine.

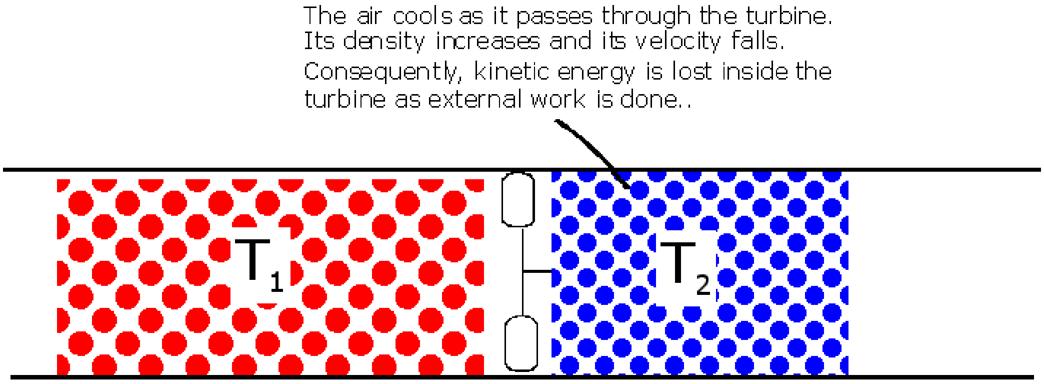


Figure 16. The turbine is not just a heat engine: it acts as a heat engine in parallel with a device that converts translational bulk kinetic energy into external work.

Air at dew point

Temp before turbine	Temp after turbine	Power output (w)	Measured efficiency (550 w blower)	Maximum efficiency predicted by Carnot equation Efficiency= $1-(T_c/T_H)$	Comment
18.47 °C = 291.47 K	18.11 °C =291.11 K	7.25	**1.32%**	**0.12%**	The bulk of the increase in efficiency can be accounted for as a release of latent heat.

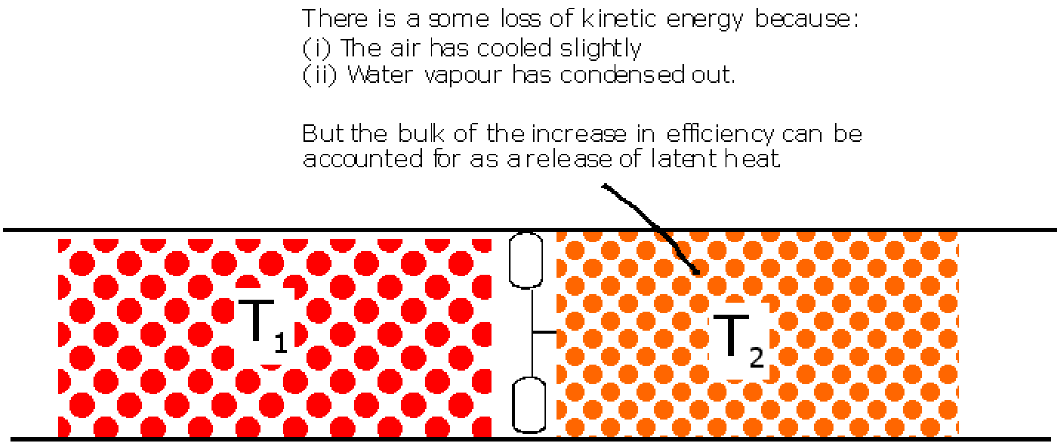


Figure 17. When dew point air passes through the turbine, the bulk of the additional efficiency comes from the liberation of latent heat.

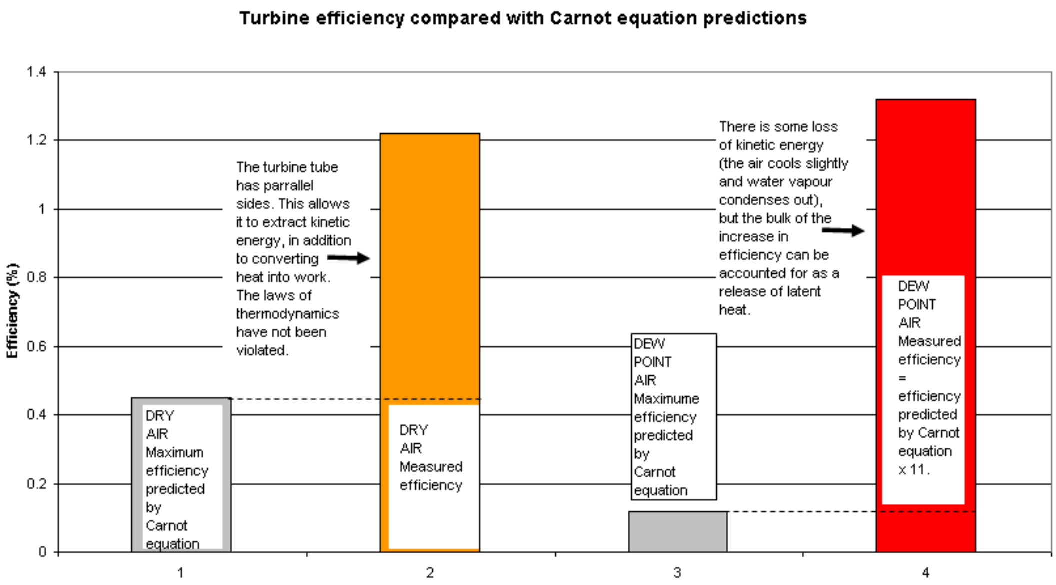


Figure 18. This chart summarises ***the illusion*** that a latent power turbine can be more efficient than a Carnot engine.

Conclusion

The experiments described in this report were carried out using small-scale apparatus, where viscous drag and other forms of friction almost swamped the results. However, the experimental data shown above demonstrates that:

(1) When saturated water vapour is accelerated through a flow constriction there is a reduction in static temperature and pressure. The temperature reduction causes partial condensation and a release of latent heat

(2) If the flow constriction is provided by a simple axial-flow turbine stage, the temperature difference can generate useful work

(3) The latent heat release is absorbed by the on-going steam/air flow, increasing the static temperature and pressure immediately downstream from the turbine.

(4) Exit flow temperature and pressure at a suitable distance downstream from the turbine are similar to the entry conditions, due to the absorption of released latent heat.

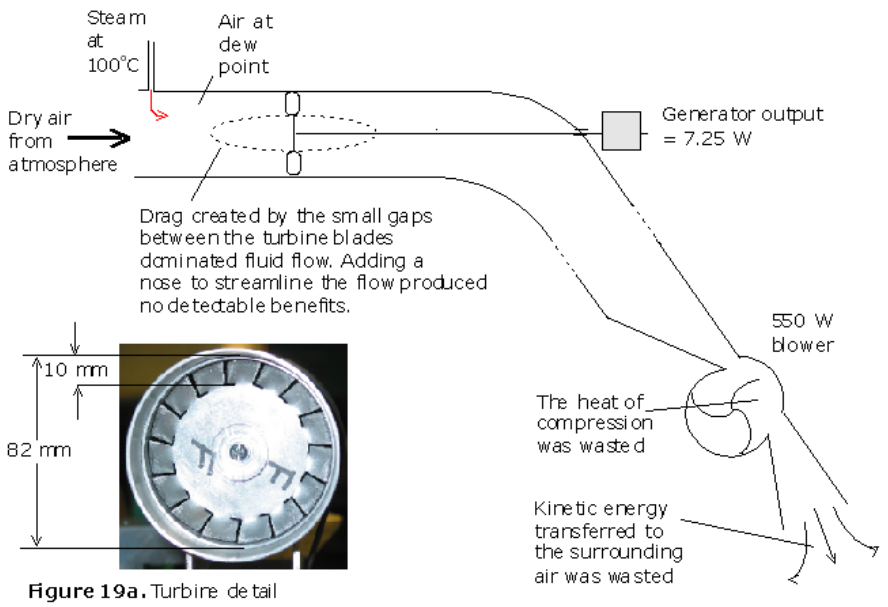
(5) Mass flow at exit from the turbine stage is less than the entry mass flow, due to the release of condensate .

This is a first demonstration of the LPT concept. Because of the temperature and pressure conditions in the turbine stage, it is expected that LPT machines may be constructed from moulded plastic and that the presence of liquid water will not cause erosion problems. Engineering solutions will be found to remove the condensate at each LPT stage.

It is clear that further tests at larger scale, to reduce the effects of friction losses, are necessary to prove the concept is commercially viable. The working concept is: a number of LPT stages in series can be used to absorb a significant proportion of the available latent heat in the exhaust steam from a primary power cycle.

APPENDIX 1

A proposal for the next stage in PL Turbine development



Figue 19. The small size of the proof of concept rig meant that drag severely restricted the power output.

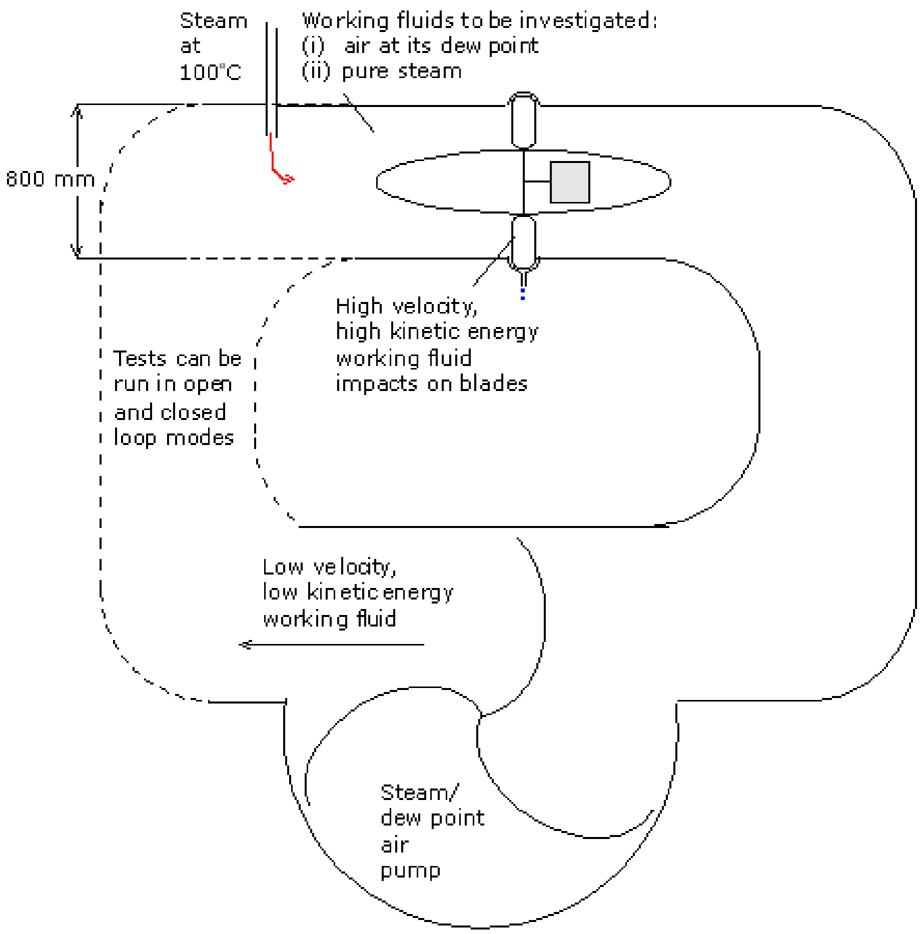


Figure 20. We suggest that a Mark II rig, incorporating a turbine diameter scaled up by a factor of ten will provide sufficient evidence for a financial risk assessment to be made, prior to building a commercial sized prototype. For the initial experiments, the 100°C steam source could be a 12 kW "off the shelf" steam generator. Drag and other losses can be separated out by comparing open and closed loop system results.
Note: The illustrated pump and turbine designs are not prescriptive. For example, the turbine could be similar to a Pelton wheel.

APPENDIX 2

A note on the use of Mollier charts

Water may be a very common substance, but is surprisingly complex - whether in its solid phase as ice, in its liquid phase, or as gaseous steam. In power plant based on steam as the working fluid, which is the case in the great majority of thermal power-generating stations, part of the cycle usually involves both gaseous steam and liquid water present at the same time. This makes the situation more complicated.

Rather than using steam tables in such instances, it is often easier to use a Mollier chart, at least at first. This is a graph of the enthalpy of steam versus its entropy. (To be more precise, the chart is usually of specific enthalpy ***h*** versus specific entropy ***s***, where 'specific' means 'per unit mass'.). To clarify: enthalpy ***h*** is effectively the energy present in a unit mass of the steam and/or water. Putting this another way, it is the capacity of the substance for doing work. It is thus a very important property of the substance in any consideration of power plant.

Entropy **s** is a property of a substance such that the change of entropy in a reversible process is equal to the heat supplied divided by the absolute temperature. A reversible process is one that involves no friction losses, and is the most efficient way of getting from one state to another. Of course, perfectly reversible processes never occur in practice, but we always aim towards reversibility, treating the perfectly reversible process as an ideal we seek to achieve.

In a power plant such as a steam turbine, once the steam has passed through the nozzles it is expected that very little heat will be lost - ideally none at all - and there will be very little friction loss. If both of these conditions are met, the entropy will remain constant. This is represented on the Mollier chart by a vertical line. If the entry conditions to the turbine are known, this vertical line can followed downwards to the exit conditions. It is then straightforward to read off the change in enthalpy from inlet to exit. In practice, some allowance has to be made for the fact that no real process will be reversible, so the entropy will not be exactly constant, but will increase somewhat from entry to exit; but nonetheless the chart is a very useful and direct way of finding the work available per unit mass of steam.

When Mollier charts are used to estimate the performance of Latent Power Turbines, two extra factors need to be taken into account:
(i) The phase change is synonymous with a large step change in entropy. Consequently, the line joining the entry and exit conditions slopes to the vertical; and
(ii) There is also a large step change in internal energy. This needs to be allowed for when interpreting the change in enthalpy.

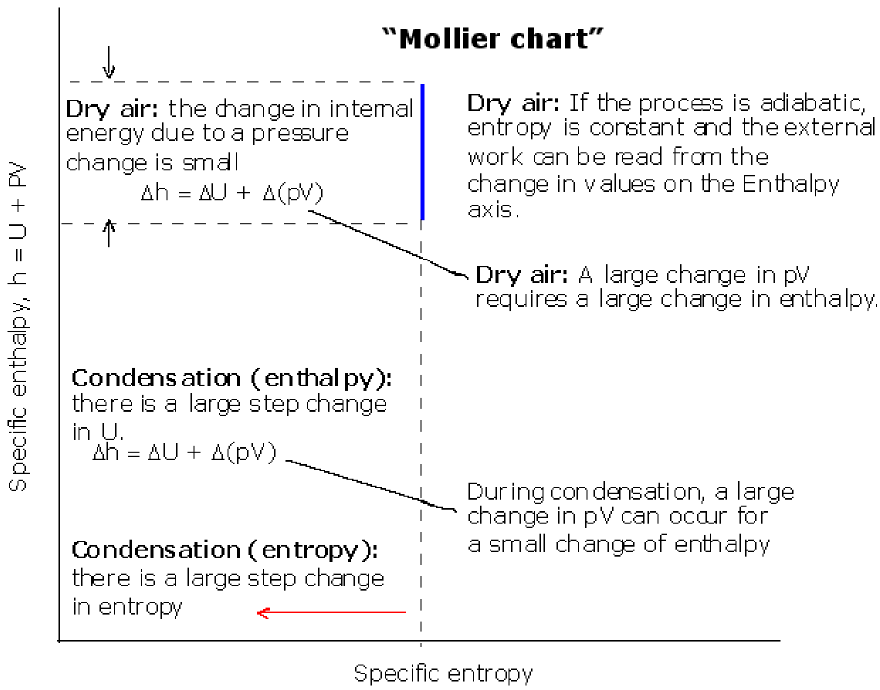


Figure 21. This annotated sketch of a Mollier chart shows the addition factors that need to be taken into account when predicting the performance of Latent Power turbines.

APPENDIX 3

This is the set of instructions used by the Lancaster University students to generate Figure 3.

Ideal sequence of events at each stage in the energy extraction and conversion chain

(i) **First acceleration** Saturated water vapour accelerated to (say) 10 m s^{-1} using a kinetic energy generator.

(ii) **Second acceleration** Vapour is funnelled, increasing the velocity of the vapour to (say) 150 m s^{-}

(iii) **Vapour gives up KE** We assume that on impact with the turbine blades, all of the translational kinetic energy (KE) of the saturated vapour is converted into rotational KE possessed by the turbine blades.

(iv) **Vapour cools** Because external work has been done, the vapour cools, so that total energy is conserved. *We estimate the drop in temperature by treating the vapour as a gas and using the formula:* Loss of KE = temperature drop x mass x specific heat of steam. NOTE For the first calculation in the sequence, we consider 1 kg of saturated vapour, but this mass has to be reduced later, as steam condenses out.

(v) **Vapour is seeded and re-heated** We assume the latent heat released is equal the KE given up when the vapour impacts on the turbine blades. (If more latent heat was liberated, we would be defying the laws of thermodynamics. If less latent heat is liberated, the vapour would remain slightly super-cooled. After several stages of this increasing super-cooling, the vapour would become so unstable, that additional condensation would take place, rectifying the instability.)

To calculate the fractional mass of vapour Δm *condensing, we use*:
Loss of KE = latent heat of steam x Δm.
This loss of mass causes a reduction in the density and vapour pressure of the steam. *To calculate the drop in saturated vapour pressure we use:*
New pressure = Original pressure x (Original mass - Δm)/ Original mass
To determine the new temperature after rejuvenation, we use saturated vapour pressure tables, reading off the temperature corresponding to our calculated value for the saturated vapour pressure.

Your project tasks

(i) Carry out a sequence of calculations, similar to above, taking the series down to 0^oC. For convenience, I suggest that you assume in each case that the impact velocity is 150 ms^{-1}. For comparison, I suggest that you repeat the calculations for (say) the first five stages, for a system having an impact velocity of 300 ms^{-1}.

(ii) It would be interesting to look at the comparative performance of a vapour that behaves as an ideal gas. I.e., you carry out an iterative series of calculations for stages (i) to (iv) above, but omit the seeding stage (v).

(iii) Plot a family of graphs to display your data concisely.

(iv) Preferably, store your data in columns, using Microsoft Excel. This will allow later workers, including Dick and myself, to build on your work.

Seeded vapour turbo-generators; Efficiency estimates

Data values used

Specific latent heat of steam (100^oC) = 2.3×10^6 J kg^{-1}
Specific heat capacity of steam (constant pressure) = 2×10^3 J kg^{-1} K^{-1}
Density of steam at 100^oC = 0.6 kg m^{-3}
Atmospheric pressure = 1.0×10^5 Pa.

Kinetic energy rejuvenation: sample calculation
To calculate the pressure drop required to generate a velocity of 10 m s^{-1} we use Bernoulli's equation for a flowing fluid

$$p + \tfrac{1}{2}\rho v^2 = \text{constant}$$

Where p is the pressure at a point, ρ the density of the fluid and v the flow velocity at that point.

This tells us that to gain a steam velocity of 10 m s^{-1} the pressure drop required is
½ x 0.6 x 10^2 = 30 Pa.

Thermal energy rejuvenation: sample calculation

Assuming the vapour impacts on the turbine blades at 150 m s^{-1} and that all of the KE is extracted, the energy lost by 1 kg of saturated vapour is 0.5 x 150^2 Joules.

To calculate the fractional mass of vapour Δm condensing, we use:
Loss of KE = latent heat of steam x Δm

0.5 x 150^2 = 2.3x10^6 J kg^{-1} x Δm

Δm = 48.9 x 10^{-4} kg = 0.005 kg approx.

To calculate the drop in saturated vapour pressure we use:
New pressure = Original pressure x (Original mass - Δm)/ Original mass

= 1.0 atmosphere. x (0.995/1.000)
= 0.995 atmospheres
NOTE I've worked in atmospheres here, simply because the saturated vapour tables I have to hand are in atmospheres.).

On inspecting my tables, I find that this corresponds to a new temperature of 99.85 ^{o}C

Temperature drop that would have occurred without seeding
KE lost by 1 kg = temperature drop x heat capacity of steam (@ approx constant pressure)
0.5 x 150^2 = temperature drop x 2 x 10^3
Temperature drop = 5.6 K
Final temperature = 94.4 ^{o}C

REFERENCES

1 Patent: GB 2427249 “Combined power generator and water desalination plant”. This has been granted.

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