Use of Convergent Nozzle to convert Enthalpy into Kinetic Energy

and Solar Energy into Electricity in the Convective Energy Conversion Cycle

Summary

The author proposes a new cycle for the conversion of solar energy into electricity using natural convection. The convective energy conversion cycle uses sealed ground level solar air collectors and could be developed for large scale generation. In previous proposals on this website there has been one crucial missing link. A convergent nozzle allows efficient conversion of the enthalpy of warm air flow into kinetic energy. Its addition immediately pre turbine to CECC should allow conversion of solar energy into electricity with good efficiency. The author asserts that all the changes involved are subject only to the first law of thermodynamics and could allow the conversion of solar energy into electricity with an overall efficiency of over 50%.

Introduction

The author has published a series of proposals on this website for the conversion of solar energy into electricity using a 'convective energy conversion cycle'. They involve the use of a sealed solar air collector to produce a flow of rising warm air. The air flow then passes through a turbine where it emerges cooler and denser and falls under gravitation to re-enter the base of the solar collector to complete the closed cycle. The author has asserted that this energy cycle will have high efficiency for conversion of solar energy into electricity as the only major energy loss is through the outer containment.

No experimental work has been conducted. The series of proposals has been circulated to many leading experts in renewable energy, thermodynamics … and published on the Internet and has generated extensive private correspondence. After several detailed, constructive, courteous exchanges with one particular adversarial correspondent [1], the author is now persuaded that there has been a recurrent serious mistake in earlier proposals. It has been repeatedly asserted that a conventional air turbine or wind turbine will absorb the excess heat energy (enthalpy) in a flow of warm air. This is not the case.

A convergent nozzle needs to be added to the warm air flow immediately pre-turbine. The nozzle converts the excess enthalpy in the warm air flow into kinetic energy which can then be efficiently absorbed by the turbine.

Convergent Nozzle

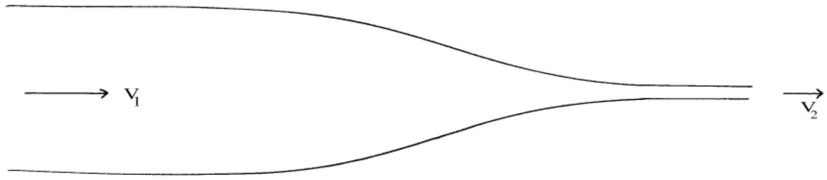


Figure 1

When a gas flowing down a pipe of cross-sectional area A_1 (as in Figure 1) encounters a change in the cross-sectional area to A_2 there is a change in the gas velocity such that

$$V_2 = \frac{A_1 . V_1}{A_2}$$

As the gas flows through the narrowing neck of the nozzle, enthalpy is converted into kinetic energy such that

$$H_1 - H_2 = \tfrac{1}{2}V_2{}^2 - \tfrac{1}{2}V_1{}^2$$

Where H_1 is the original enthalpy and H_2 is the enthalpy in the throat of the nozzle.

As the gas flows through the nozzle, the velocity increases continuously until it reaches a maximum value in the throat. The pressure, temperature and density all decrease in the direction of flow. Flow through a nozzle involves no work done and is adiabatic. The conversion of enthalpy into kinetic energy in a nozzle has an efficiency of 90-99%. (For further information on convergent nozzles see Appendix 1- Pages 8-9.)

Convective Energy Conversion Cycle

A convergent nozzle as described above needs to be added immediately pre-turbine to the configurations described in earlier proposals. The sequence is then as in Figure 2.

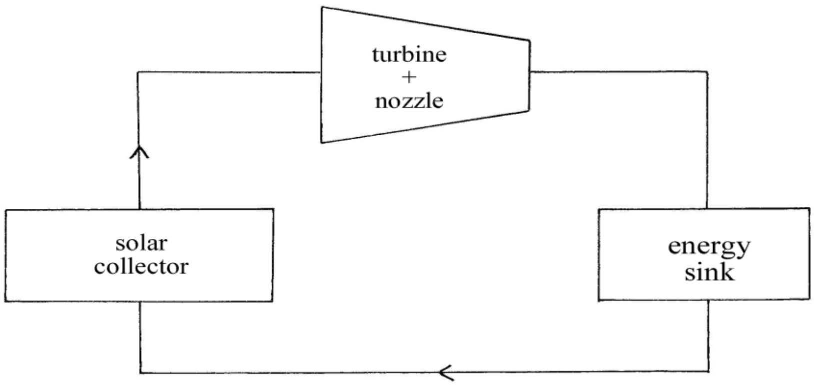


Figure 2

Air flows through the sealed solar collector by natural convection. Warm air rises and generates pressure on the convergent nozzle. As the air flows through the nozzle its excess enthalpy is converted into kinetic energy. The air flow reaches high velocity in the throat of the nozzle where it impinges on a conventional air/wind turbine. Such turbines in ducted flows can have an efficiency of over 80% [2,3]. The air post-turbine is cooler and denser and will fall under gravity surrendering its residual excess energy to an energy sink if needed. It then returns to the base of the solar collector to complete the cycle.

Optimal Nozzle Orientation

As warm air passes through the nozzle its density falls in the direction of flow. The ideal lineage for the nozzle in CECC would then be vertical as shown in Figure 3 so that the lowering density through the neck of the nozzle reinforces the buoyancy of the rising warm air.

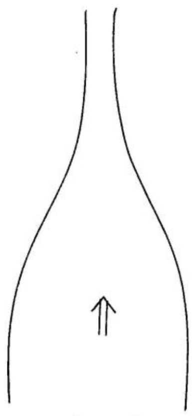


Figure 3

CECC Model Experiment

Consider the configuration shown in Figure 4. The dome could be of any dimensions suitable for laboratory or outside experiment. The vessel is of glass, contains air at atmospheric pressure and is sealed at ground level. The inverted funnel is also of glass anchored to the base at intervals along its circumference. The ground surface is covered with a solar absorber so that incident solar energy is taken up with over 90% efficiency. What happens to the solar energy that is absorbed by this configuration?

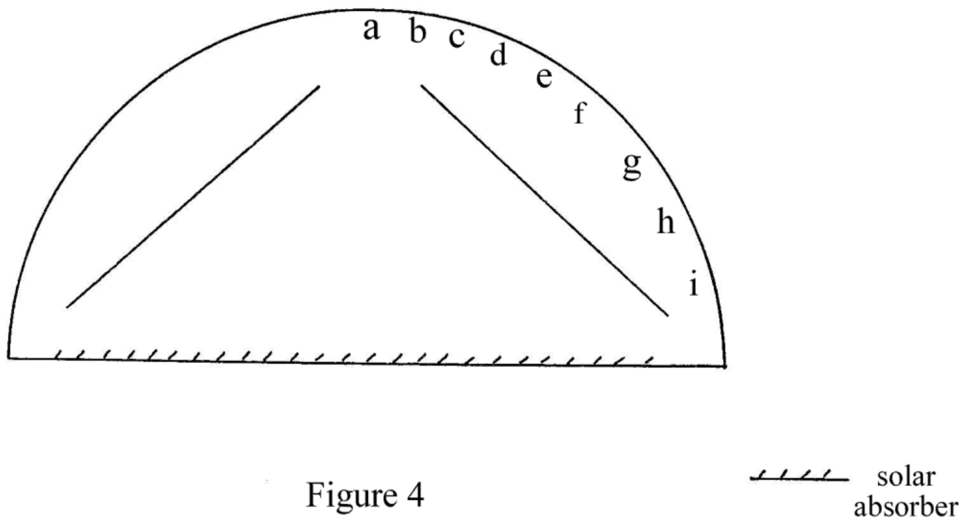


Figure 4

The energy that is continuously being taken up by the absorber has to be dissipated from the apparatus. It can only be lost by conduction, convection or radiation. One would expect the solar absorber to reach a temperature of perhaps 100C in sunny conditions – at this temperature there will be very little loss by radiation. There will be some loss by conduction along the ground along the perimeter of the vessel.

The main heat loss will be by convection. Air molecules in the vicinity of the absorber will be warmed by collision with the absorber surface. The warm air is lighter and rises due to buoyancy drawing in cooler air from the sides to replace. The rising warm air is channelled by the funnel to the top of the dome (a). Here air molecules will collide with the glass which is cooled by ambient air. Heat will be transferred from the warm air molecules through the glass by conduction. The air inside the vessel is thus cooled and is cooled further as it passes to b, c, d, e, f, g, h and i and is then drawn into the absorber.

Over 90% of the solar energy taken up by the absorber will take part in this convective heat flow. Since there is flow it should be possible to intercept this flow using a turbine. If a wind turbine was placed in the narrowest part of the funnel it could absorb the kinetic energy in the air flow.

Note that the funnel in Figure 4 is also a convergent nozzle. Air that has been warmed by the absorber has buoyancy and exerts a pressure driving air flow through the funnel/nozzle. As it travels through the nozzle some of the excess enthalpy of the warm air is converted into kinetic energy as it reaches the throat of the nozzle.

The author has insufficient background in compressible flow/fluid mechanics/heat transfer but estimates that if the diameter of the solar collector is about 5-10 times the diameter of the throat of the nozzle, then it is possible to convert ALL the enthalpy above ambient of the rising warm air into kinetic energy in the throat of the nozzle. The air velocity through the throat of the nozzle would be of the order of 200m/s, 500mph. Specialist air turbines that have been designed to extract energy efficiently from this high velocity air flow would need to be used eg ram air turbines used as an emergency power source in aircraft.

The author requests that research work be conducted on the model above using thermometers, flowmeters and air turbines to better understand the parameters that maximise the velocity of air through the throat of the nozzle. It should be possible to convert incident solar energy into electricity with high efficiency using this simple model.

CECC Alternative Configurations

If the principles described hitherto can be demonstrated to work with good efficiency in the model experiment outlined, there are a wide variety of alternative configurations that could then be developed.

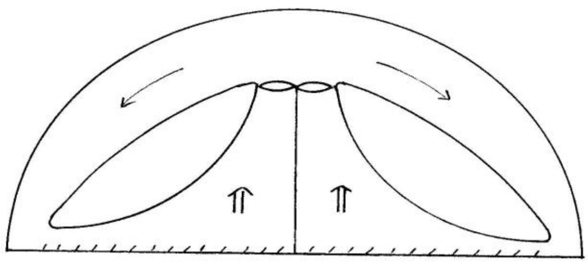


Figure 5

Figure 5 makes some attempt at improved aerodynamic design for the nozzle and the cool air flow inside the outer containment.

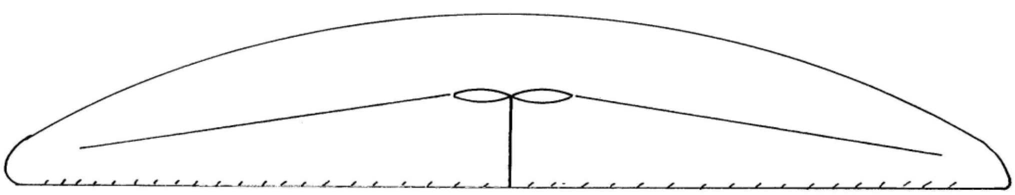


Figure 6

Figure 6 illustrates a shallow dome which would reduce energy losses to ambient air through the outer containment and would reduce visual impact for a large-scale structure. It also offers a lower height for turbine anchoring and greater stability.

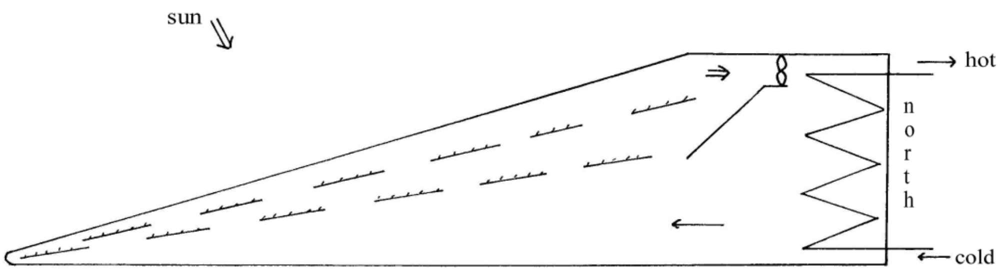


Figure 7

Figure 7 again describes a configuration that could be suitable for large-scale operation. The convergent nozzle and turbine are sited at the top of the structure to take advantage of the lower density through the nozzle. The solar absorber is presented as two layers unsymmetrically placed to allow maximum capture of solar energy, good air flow and efficient heat exchange. An energy sink could also be included if needed with water circulating by thermosyphon.

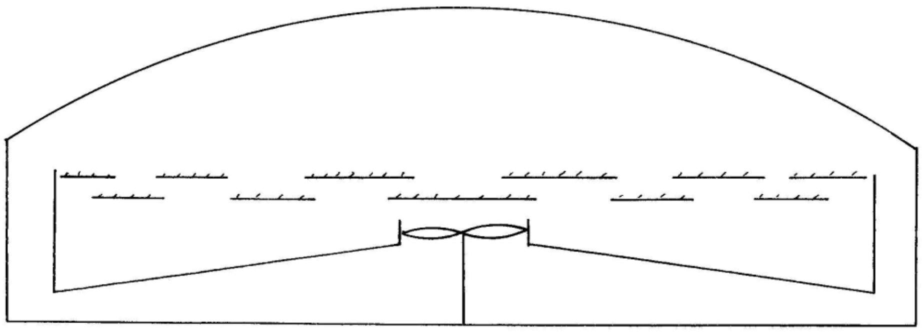


Figure 8

Figure 8 sketches a system that could allow ground level electrics with robust anchoring for the nozzle and turbine. The raised solar absorber warms air in its vicinity which rises. This draws cooler air from beneath which must pass through the convergent nozzle and turbine generating electricity. The structural material for the nozzle and sides need not be transparent. An energy sink could be placed in the annulus if needed.

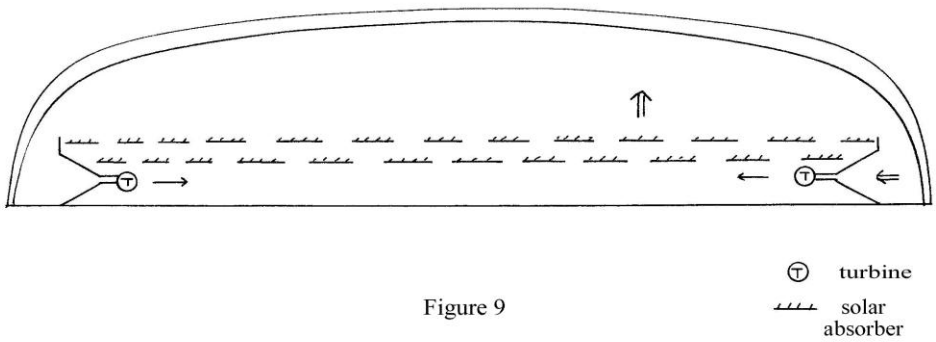


Figure 9

In Figure 9 the solar absorber warms air in its vicinity which rises drawing air through the convergent nozzle and turbines. This configuration again gives the advantage of ground level electrics.

Warm Air Turbine

Steam turbines convert the enthalpy of water vapour at high temperature and pressure into electricity. The steam flows through successive stages of stationary nozzles where its enthalpy is converted into kinetic energy. The flow of steam now at very high velocity then impacts on the blades of the turbine wheel producing rotational energy. The enthalpy of the steam is converted into electricity with 90-99% efficiency in the steam turbine. (See also Appendix 2 – Page 10.)

There is no reason in principle why a steam turbine could not be driven by warm air under pressure. Turbines could be built that use warm air from a large solar collector at up to 30C above ambient and 1.1 atmospheres pressure as their feedstock. Their much lower power density would mean large dimensions and light materials with a low moment of inertia ... but there is no reason in principle why they should not have efficiencies comparable to the steam turbine.

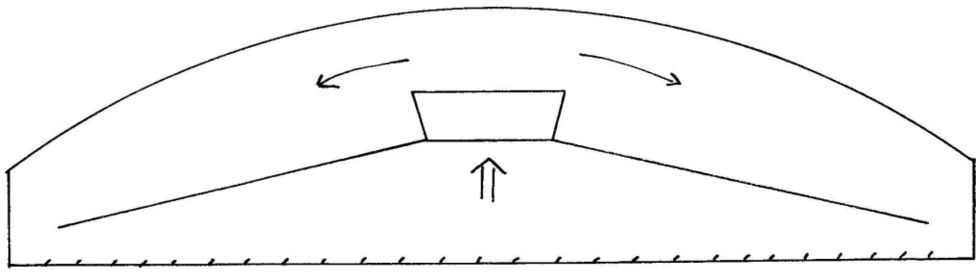


Figure 10

Figure 10 gives an outline of possible large scale conversion of solar energy into electricity using the preferred model experiment configuration. The absorber takes up solar energy and warms air in its vicinity which rises and accelerates as it flows through the main structural nozzle. As it flows through the warm air turbine it will be accelerated to very high velocity by the turbine nozzles. Virtually all its enthalpy above ambient is converted into kinetic energy and then into electricity. The pressure that drives the air through the turbine is simply natural convection.

Efficiency of CECC

What would be the overall efficiency for the conversion of solar energy into electricity using the convective energy conversion cycle and a converging nozzle to convert the enthalpy of warm air flow into kinetic energy immediately pre-turbine as described in this paper?

Many classical physicists will insist that the maximum efficiency for the conversion of heat into mechanical energy is given by Carnot's Theorem as $\Delta T/T$. If the temperature difference between the hottest and coolest parts of the cycle is say 30C, then the maximum efficiency is 10%.

It is the author's assertion however that the convective energy conversion cycle described on this website represents a completely different embodiment. It is driven by natural convection – buoyancy and gravitation. In the classical thermodynamic cycles there are usually 4 stages with some or all involving changes of volume, pressure and temperature. CECC doesn't have such stages – indeed all changes take place within the same enclosure at macroscopic constant volume. There is no need for an energy sink. Any losses due to equipment inefficiencies will be lost through the walls of the containment. Indeed even these losses could be minimised by judicious choice of materials and double glazing.

It is the author's assertion that each successive change that takes place in CECC and the nozzle is subject simply to the first law of thermodynamics. The efficiency of each stage could be as follows:

transmittance of solar energy through glass	90%
absorption of incident solar energy by coated surface	90%
conversion of enthalpy of warm air into kinetic energy in the nozzle	90%
conversion of kinetic energy of air flow into electricity in the turbine	80%

This could give an overall efficiency of conversion of solar energy into electricity of over 50%.

Further Work

This paper gives a qualitative and descriptive indication of principles by which it may be possible to convert solar energy into electricity with good efficiency using sealed ground level structures. The author has limitations in background expertise and needs people to develop the theoretical framework. Also no experimental work has been conducted. The author asks for individuals who have appropriate skills and facilities to build test structures such as Figures 4 – 6 to research and develop the proposals.

References

[1] Private correspondence with Stephen Noe, P.E., Texas, USA.

[2] J. Schlaich, The Solar Chimney, Edition Axel Menges, Stuttgart, Germany, 1995, p20-21, 37.

[3] Janet Ramage, Energy, Oxford University Press, 1997, p225.

Dr Alan Williams *July 2006*

APPENDIX 1 **Convergent Nozzle**

1. Thermal Physics (1986), C. B. P. Finn, p52

Flow through a nozzle

When a gas flowing down a pipe encounters a change in the cross-sectional area, there is a change of gas velocity. We utilise this effect frequently in engineering and in particular in a turbine where we 'throw' the gas on to the turbine blades with a high velocity. The incoming gas (steam in the case of a steam turbine) is speeded up by passing it through a nozzle, as in Fig. 3.7. No shaft work w is done, the system is assumed to be horizontal and we further assume that no heat q enters the system as the gas flow is too rapid for this to be appreciable. Equation [3.16] then becomes:

$$v_1^2 - v_2^2 = 2(h_2 - h_1) \qquad [3.18]$$

which relates the velocity change to the enthalpy change.

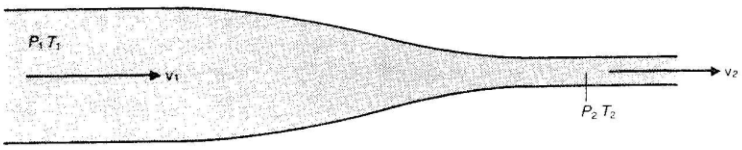


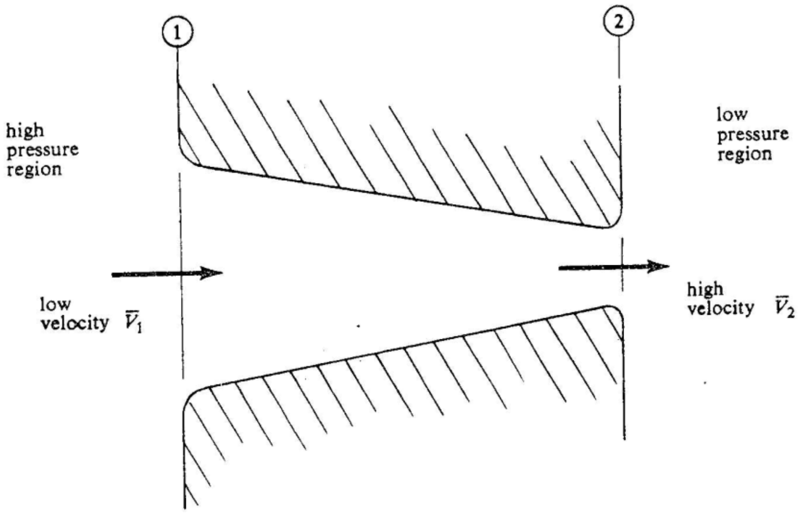
Fig. 3.7 A steady flow process through a nozzle.

2. Thermodynamics and Heat Power (1994), Kurt C. Rolle, p376

10–4 NOZZLES AND DIFFUSERS

Fluids such as gases and liquids are carriers of energy, and during their flow through pipes, conduits, channels, or other conveyors, it is frequently desired to convert the energy to other forms. For instance, high-temperature gases (containing internal energy) may be accelerated to increase the kinetic energy by forcing the gases through a restriction called a **nozzle.** The kinetic energy increase would be done at the expense of internal energy or enthalpy.

FIGURE 10–12 Typical converging nozzle



3. Thermodynamics (1976), Abbot and Van Ness, p193

$$\frac{u_2^2 - u_1^2}{2} = -(H_2 - H_1)$$

This equation expresses the fact that the velocity change caused by flow through an adiabatic nozzle is directly related to the enthalpy change for the process.

The velocity given by this equation can very nearly be attained in a properly designed nozzle.

4. Fluid Mechanics with Applications (1998), Esposito, p565

$$\frac{P_2}{P_1} = \left(\frac{\rho_2}{\rho_1}\right)^k$$

This equation shows that as the pressure decreases in the direction of flow. the density decreases.

5. Equilibrium Thermodynamics (1997), C. J. Adkins, p48

3.8.3. *The ideal nozzle*

The ideal nozzle is the opposite extreme from the perfect throttle. Here, the intention is to create as high a velocity as possible by keeping friction and turbulence small. Often, the kinetic energy before the nozzle is small and we again have

$$h_1 - h_2 = \tfrac{1}{2}\mathscr{V}_2^2 \qquad [(3.40)]$$

but now there is a large drop in enthalpy and a high kinetic energy after expansion.

In a jet engine the w and z terms of (3.37) are unimportant. The fuel provides a large q and so raises to a high value the specific enthalpy of the gas which has been drawn into the system. This is accompanied by a large rise in pressure. The high enthalpy fluid is then expanded in the nozzle at the back of the engine, in the course of which the enthalpy is reduced and the energy converted into kinetic form in the emerging gases. The enthalpy is never reduced to its initial low value but the whole process tends towards a complete conversion of q into kinetic energy. The purpose of after-burners on a jet engine is to increase $\mathscr{V}_2$ still more by adding yet more heat after the initial expansion.

3.8.4. *The turbine*

In the turbine, the object is to obtain the greatest possible external work. In this case, the device is designed to reduce kinetic energy terms to a minimum and (3.37) becomes

$$h_1 - h_2 = w. \qquad (3.41)$$

6. Thermodynamics and Heat Power (1990), Irving Granet, p125, 325

A nozzle is a static device that is used to convert the energy of a fluid into kinetic energy. Basically, the fluid enters the nozzle at a high pressure and leaves at a lower pressure. In the process of expanding, velocity is gained as the fluid progresses through the nozzle. No work is done on or by the fluid in its passage through the nozzle.

For most nozzles, the efficiency varies from 90% upward, with larger nozzles having higher efficiencies.

APPENDIX 2 Steam Turbines

1. Steam Plant Operation (1998), E. B. Woodruff, H. B. and T. F. Lammers, p517, 523

The turbine makes use of the fact that steam, when passing through a small opening, attains a high velocity. The velocity attained during expansion depends on the initial and final heat content of the steam. This difference in heat content represents the heat energy converted into kinetic energy (energy due to velocity) during the process.

As described previously, a steam turbine takes the thermal energy of the steam, which is provided by a boiler, and converts it into useful mechanical work by means of the steam expanding as it flows through the turbine. Steam is introduced into the turbine through small stationary nozzles, where the steam expands and reaches a high velocity. This process converts the thermal energy in the steam to kinetic energy as it passes through the nozzle openings and moves the turbine blades, which are attached to the rotor.

2. Power Plant Control and Instrumentation (2000), David Lindsey, p15-16

In plants using a turbine, the energy in the steam generated by the boiler is first converted to kinetic energy, then to mechanical rotation and finally to electrical energy.

In the turbine, the steam is fed via nozzles onto successive rows of blades, of which alternate rows are fixed to the machine casing with the intermediate rows attached to a shaft (Figure 2.2). In this way the heat energy in the steam is converted first to kinetic energy as it enters the machine through nozzles, and then this kinetic energy is converted to mechanical work as it impinges onto the rotating blades.

As the steam travels through the machine in this way it continually expands, giving up some of its energy at each ring of blades. The moment of rotation applied to the shaft at any one ring of blades is the multiple of the force applied to the blades and mean distance of the force.

By the time it leaves the final stage of the turbine, the steam has exhausted almost all of the energy that was added to it in the steam generator

3. Thermodynamics (1976), Abbot and Van Ness, p194

Example 6.7. The isentropic expansion of a fluid through a nozzle as discussed in the preceding example produces a fluid stream of increased kinetic energy. This stream can be made to impinge on a turbine blade so as to provide a force to move the blade. The stream thus does work on the turbine blade at the expense of its kinetic energy. This is the principle on whieh the operation of a turbine depends. A series of nozzles and blades is arranged to expand the fluid in stages and to convert kinetic energy into shaft work. The overall result of the process is the expansion of a fluid from a high pressure to a low pressure with the production of work rather than the production of a high-velocity stream.

4. Fundamentals of Thermodynamics (1945), Adams and Hilding, p264

Experiments have disclosed that efficiencies of actual steam turbine nozzlès range from 0.90 to 0.97.