

Energy recovery - Captation and storage of carbon dioxide on Fossil fuel vehicle engines

Introduction

The previous section focussed on large fossil fuel power plants. In these land based installations, it is possible to deploy large and sophisticated means of energy recovery (heating of residential buildings, vapour generation or use of Rankine or combined cycles) as well as carbon dioxide captation (involving chemical or physical solvents), processing and storage of toxic gases produced during fuel combustion. Downstream of these facilities, toxic gases, particularly, carbon dioxide can be injected into a pipeline or into the ground.

For mobile energy production units (road or maritime), energy recovery and sour gas treatment conditions are considerably less easy requiring means adapted to the situation.

In this twenty first century, the environment pollution is such that electrical vehicles are foreseen as the main solution for resolving some of the environment damages. However, this does not take into account all the new constraints which are going to be generated in a world centred on electrical energy. To the contrary, the future may progressively organize a mix of energy for vehicles including electricity, fuel cells, hydrogen, powered air and fossil fuel. Electrical batteries are not at all adapted to large engines (trucks, trains, boats) for which, combustibles like hydrogen, natural gas and LPG may be more adapted to the situation. To severely reduce the CO₂ concentration into the environment, the use of fossil fuel may only be permitted if fuel engines increase significantly their thermal efficiency and are designed to capture the CO₂ produced at its source of emission and to store it until a delivery point.

Types of engine and operating modes

A road vehicle (car, truck, bus, etc.) is generally driven by a piston engine. It can however, occasionally, be driven by a gas turbine especially in the case of high power demand (truck, bus). Boats and trains are provided with both types of engine.

Each machine type has its own advantages if one considers the cost, the volume, the weight, the noise emission, the vibrations induced and the maintenance requirement. In both cases, machines may operate either at variable speed and power adapted to the instantaneous demand (idle to full load) or at constant speed and power (or a selection of operating points) allowing the operation to a point of best efficiency or overall optimization. These machines are then associated to a system storing the

energy excess. The stored energy is then distributed whatever the main engine is running or not.

Energy recovery

With these two types of engine, a significant part of the heat generated during the combustion is released into the atmosphere. As described in a few documents, this heat could be recovered in an auxiliary thermal cycle (Rankine or equivalent) producing mechanical energy and helping to reduce the power supplied by the main engine. In the case of a reciprocating engine, the temperature of the burnt gases is very high because the air dilution of the gas is low (stoichiometric combustion). On the other hand, in the case of a gas turbine, the temperature of the fumes is lower but the dilution rate greater. If one gains in theoretical efficiency (Carnot efficiency - ratio of hot and cold absolute temperatures) in the first case, the quantity of combustion air is more important in the second case. It is difficult at this stage to determine which machine can provide the best overall performance within considering its exact characteristics.

Rankine cycle

The operation of a Rankine cycle requires at least four elements in which a refrigerant fluid with phase change (gas-liquid) circulates in a closed loop. After pressurizing the liquid refrigerant with a pump A2, the liquid is sent to an evaporator that converts the liquid into a gas phase thanks to the heat taken from the outside of the evaporator (in the present case, heat is provided by the exhaust gas). Brought to a high temperature and high pressure, the gas is let down through an expander A1 whose performance increases with an increase in temperature and pressure at the inlet of the expander. At the expander outlet, the gas is sent into a condenser permitting the liquefaction of the refrigerant fluid. In the present case, the condenser may be cooled by the environment air.

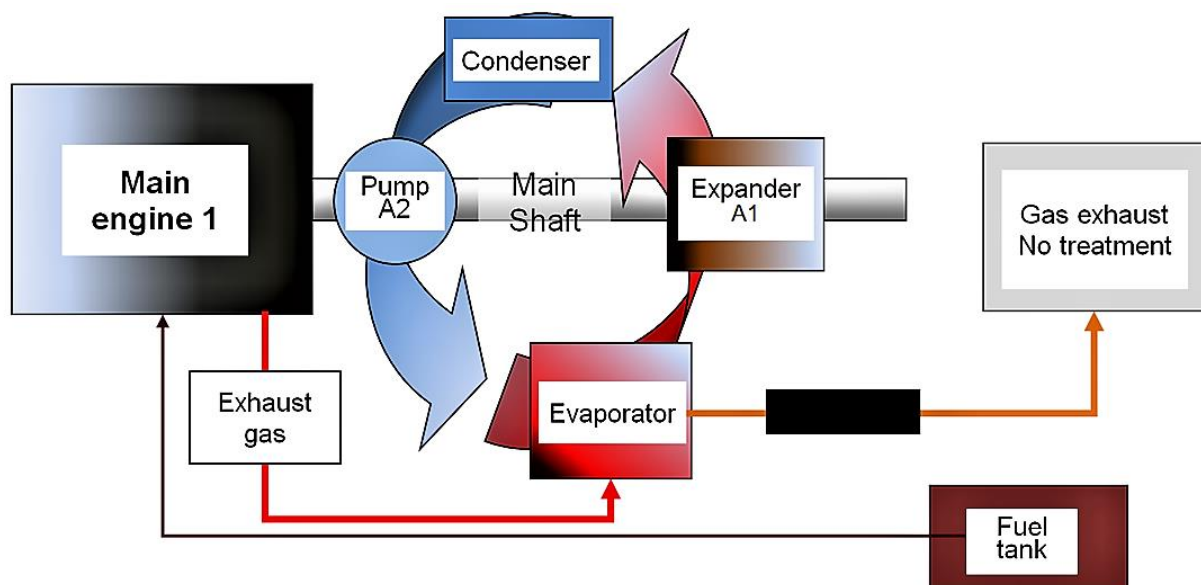


Figure 1 – Exhaust gas passing through the evaporator of a Rankine cycle

The liquid pressure is raised again by pump A2 for a repeat of the cycle.

Energy storage options

The energy storage could be done in different ways: electric, kinetic, pneumatic (storage of air or burnt gases at high pressure – A potential energy) or other means. If electricity was selected it could be combined with photovoltaic cells. The pneumatic system can, however, provide other advantages; in particular, it allows the captation of the toxic gases resulting from the combustion usually released into the atmosphere. This may be carried through a compression / expansion system involving the burnt gases.

Cycle of a pneumatic system activated by combustion gases

After passing through the evaporator of a Rankine cycle, combustion gases are cooled down before and after a pressurisation process B1 (First cycle sequence). The cooling process consists in transferring the heat to either a thermal cycle in view of producing energy or to expander B2 (Last cycle sequence) for increasing the delivered energy. Gas cooling before pressurisation permits to reduce the compression energy while gas cooling after pressurisation permits to increase the solubility of the sour gases into a solvent (Tank A – Intermediate cycle sequence). Combustion gases are pressurised to around 700 bars (pressure usually considered for hydrogen storage – tanks made of composite materials). In the storage tank A, during and following the compression process, the burnt gases are brought into contact with a physical solvent distributed into droplets with an extremely small diameter for increasing the surface exchange (Circuit 1 – MeOH captation).

Two points should be noted:

- The cooling of the combustion gases at the compressor inlet (B1) may produce **water condensation** which in turn may generate some corrosion inside the cooler and at the compressor entrance. Several solutions are available to handle both the compression (erosion) and the aggressiveness of the two phase mixture.
- The **vaporisation of the water** phase occurring during compression leads to an isothermal process reducing the absorbed compression power.

The gases burnt in stoichiometric condition (oxygen molecule rate matching exactly the fuel molecule rate for complete combustion) contain the largest possible fraction of carbon dioxide, the other gases being: nitrogen, water vapour and nitrogen oxides. In a non-stoichiometric condition (air in excess to carry the heat produced by the fuel combustion), a fraction of the fumes is recycled until the combustion reaches the stoichiometric condition, therefore, to contain the largest possible fraction of carbon dioxide and to avoid the entrainment of oxygen into the tank containing the solvent. A piston engine (Engine 1 on figure 1) and a gas turbine (Engine 2 on figure 2 assuming no CO₂ enrichment) are two examples of, respectively, stoichiometric and

non- stoichiometric combustions. Note that on figure 2, the gas turbine is provided with a CO₂ enrichment line permitting a stoichiometric combustion.

The contact of CO₂, NO_x (and also a small fraction of the water phase) with the solvent droplets permits their dissolution into the solvent according to the partial pressure of each gas. After the maximum storage pressure has been reached and following a short time to permit the complete dissolution of the above gases, the liquid solvent fraction is isolated from the storage tank A which then only contains the following gases: mostly nitrogen, water vapour, a small fraction of CO₂ and traces of NO_x, argon and krypton. These last gases may later be depressurized through an expander and be released into the atmosphere.

The liquid solvent requires later on to be processed for its regeneration. In the simplest situation, the solvent (for instance, methanol) may be discharged from its maximum operating pressure (for instance, 700 bars) at a service station, for instance, during a refuelling process. Another solution is presented in a following paragraph (Solvent management and purification).

The mass of CO₂ produced is around three times the mass of the burnt fuel (bearing in mind the molecular weight of each element). The total mass may even reach four times taking into account the mass of dissolved water and NO_x. In this arrangement, there are at least two tanks (or two series of tanks) operating in alternate: one in charge (A - burnt gases in contact with the solvent) and another one in discharge (B) mode supplying an expander, this latter producing energy for the vehicle drive.

Two more points should be noted:

- For a smoother operation of the vehicle, ***it is recommended to use at least three series of tanks*** operating in a phase shift of respectively, one, two and three third of a period. In that instance, there is always one tank in a discharge mode when the other two are switching between the compression and the discharge modes.
- The solvent at a very high pressure and containing a large amount of sour gas, the ***solvent let down process provides a large amount of energy*** which may be recovered in an electrical battery or by increasing the pressure in any of the high pressure tank A or B.

Improved Rankine Cycle

In the case of a conventional Rankine cycle the heat extracted from the condenser is lost. In the present situation (figure 2), some of the heat beneficial to the lower stages of the expander B2 is taken out from the condenser of the Rankine cycle before the condenser is completely cooled down (for instance by the ambient air) to provide the larger pressure differential (actually inlet / outlet pressure ratio) for expander A1.

Solvent Management and Purification

- **An optimized working pressure has to be determined** for the final separator considering the sour gas content after purification, the energy which may be obtained during the D2 expansion, the energy eventually required to boost the sour gas into the fuel tank, the temperature after expansion D2, the risk for carbon hydrate formation and the volumetric mass of CO₂ (below or above critical pressure).

CO₂ Storage

It is assumed in the present case that the fuel is a pressurised hydrocarbon gas (natural gas or LPG). Alternatively, a liquid fuel may also be considered but its reservoir will then be separated from the sour gas (carbon dioxide) tank.

In the gas case, the fuel and the sour gases share the same storage tank separated by an elastic membrane (many industrial equipment use this very high-pressure technology: anti-pulsatory bottles for reciprocating pump protection, compressor oil sealing system, etc.). When one part fills up, the other empties and vice versa. In particular, when filling up the tank with fuel gas, it drives the sour gas mixture out of the tank at the speed at which the fuel tank is filled up. This allows the tank to operate at almost constant pressure. Therefore, in this configuration, there is no need to create a specific tank for CO₂ storage. When using natural gas, the CO₂ is stored in dense phase condition (above the critical point pressure – high volumetric mass) occupying the minimum volume in the storage tank of the vehicle or at gas station. In that pressure condition, the gas is available for exporting it into a pipeline.

Equipment summary

For the main energy recovery, are required an expander A1, a condenser, a pump A2 and an evaporator, the expander and the pump being mounted on the main engine shaft.

For the sour gas captation (mainly CO₂), are required, two tanks A and B (or several sets of tanks operating in sequence) running alternatively (one filling up with the other discharging and possibly others operating with a phase shift) for storing and treating the burnt gases, one compressor B1 for filling up the tanks, one expander B2 letting down the pressurised gases for driving the vehicle, a solvent spray pump (C) a methanol reservoir for sour gas captation and two other reservoirs one for the pure solvent and one for the contaminated solvent.

For the methanol treatment are required a turbo expander (Pump D1 and expander D2) for solvent purification and sour gas storage. Contrary to the above paragraph (No methanol treatment) there is only one methanol reservoir operating at intermediate pressure but two MeOH captation circuits operating at high pressure.

Concerning the driving shafts, shaft 1 includes the main engine, expander A1, pump A2 and compressor B1. Shafts 1 and 2 may be separated or linked together through a gear box or a hydraulic coupling depending on the main engine type and the operating mode (main engine idle or not on some occasions). The spray pump

and the turbo expander D1-D2 may be mounted on the same mechanical transmission system.

Conclusion

The overall system includes a large number of equipment significantly increasing the mass of the vehicle. On the other hand, it helps to considerably reduce the size of the main fuel engine and also the fuel consumption therefore the fuel tank (optimized main engine operation, use of a Rankine cycle, removal of some heat from the condenser for the benefit of the combustion gas expander) but, above all, it allows most of the CO₂ usually emitted to the atmosphere to be captured at the source of emission in the case of road vehicles, trains and boats, the largest CO₂ emission contributors on the planet. This system could be envisaged initially on the largest equipment that can gradually lead to a miniaturization of the system.