

SYSTEM FOR CONTROLLING A RANKINE CYCLE

5 **FIELD OF THE INVENTION**

The present invention relates to a system for controlling a Rankine cycle and to a method for producing electricity that can be implemented using this system.

10 **TECHNICAL BACKGROUND**

A Rankine cycle is a system that allows heat energy to be converted into electrical energy. The heat recovered is used to heat and then vaporize a heat-transfer fluid which is then expanded in an expansion member, typically a turbine, powering a generator. The fluid is then condensed so that the cycle can
15 be recommenced.

Rankine cycles are notably used for the production of electricity, for example in electricity power stations. Such cycles generally use water as the heat-transfer fluid.

Organic Rankine cycles (or ORCs) use organic products in place of
20 water. That makes it possible to reduce the size of the facilities and to construct low-power facilities.

At the present time, the cost of such facilities remains high because of the technologies needed for controlling them, and this is slowing the development of this technology for current applications.

25 The presence of liquid particles at the inlet to the expansion member (turbine) leads to phenomena of corrosion and erosion thereof, and to mechanical stresses liable to damage or destroy it.

The heat-transfer fluid therefore generally needs to be in the vapor state before it enters the expansion member. It is known practice, in order to prevent
30 liquid from entering the expansion member, to place a liquid – vapor separator between the evaporator and the turbine.

Document US 7,841,306 thus describes a Rankine cycle comprising a liquid – vapor separator between the evaporator and the turbine and allowing liquid droplets present in the stream coming from the evaporator to be
35 recovered and returned to a liquid reservoir placed at the outlet of the condenser.

Document DE 10 2011 009 280 also describes a liquid – vapor separator connected to a pipe returning to the evaporator.

Document WO 2007/104970 describes, in conjunction with figure 1 thereof, a known Rankine cycle comprising a liquid – vapor separator between the evaporator and the turbine. A pipe is provided to recirculate liquid from the separator to the evaporator. Furthermore, the liquid level in the separator is measured and determined to control the circuit pump, according to the demand for electrical energy. If the liquid level in the separator increases, the delivery rate of the pump decreases, and vice versa. The document then proposes to distinguish itself from this known system by allowing a fraction of liquid to enter the expansion member and by controlling this fraction using a complex control system.

Document WO 2012/130421 describes a facility adapted to recover heat from several distinct sources. The facility comprises a common liquid – vapor separator and a common turbine, and several evaporators and pumps corresponding to the various sources. The liquid – vapor separator acts as a liquid reservoir for the facility, since it is also supplied with liquid coming from the condenser.

Document FR 2976136 teaches a facility based on a Rankine cycle, provided with bypass valves in order to bypass the turbine.

There is therefore a true need to supply an electricity production system relying on a Rankine cycle capable of operating with an organic heat-transfer fluid, in which the expansion member is protected from any damage in a way that is simple and economical.

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SUMMARY OF THE INVENTION

The invention relates first of all to a system for producing electricity, comprising a closed heat-transfer-fluid circuit which comprises an evaporator, an expansion member, a condenser and a circulation pump, a generator being coupled to the expansion member, in which a liquid – vapor separator provided with a liquid reservoir is placed between the evaporator and the expansion member, the system being further provided with a control device configured to empty the reservoir if the liquid level in the reservoir reaches a maximum threshold.

35 According to one embodiment, the heat-transfer fluid is organic.

According to one embodiment, the emptying of the reservoir is performed by a liquid recirculation line feeding into the evaporator.

According to one embodiment, the control device is configured to reduce the delivery rate of the circulation pump if the liquid level in the reservoir reaches the maximum threshold.

5 According to one embodiment, the liquid level in the reservoir is kept between a minimum threshold and the maximum threshold.

According to one embodiment, the control device is configured to put a stop to the emptying of the reservoir if the liquid level in the reservoir reaches the minimum threshold.

10 According to one embodiment, the control device is configured to increase the delivery rate of the circulation pump if the liquid level in the reservoir reaches the minimum threshold.

The invention also relates to a method for producing electricity, comprising the following concurrent steps:

- 15 – heating and evaporating a heat-transfer fluid using a heat source;
 - separating the heat-transfer fluid that has undergone evaporation into a liquid phase and a vapor phase, the liquid phase being stored in a liquid reservoir;
 - expanding the vapor phase to allow the generation of an electrical current;
 - 20 – condensing the expanded vapor phase; and
 - pumping the condensed phase;
- and further comprising the following steps:
- monitoring the liquid level in the liquid reservoir; and
 - 25 – emptying the liquid reservoir when the liquid level in this reservoir reaches a maximum threshold.

According to one embodiment, the heat-transfer fluid is organic.

According to one embodiment, the emptied liquid is recirculated to the heating and evaporation step.

30 According to one embodiment, the delivery rate at which the condensed phase is pumped is reduced when the liquid level in this reservoir reaches the maximum threshold.

According to one embodiment, the liquid level in the reservoir is constantly kept between a minimum threshold and the maximum threshold.

35 According to one embodiment, the step of emptying the reservoir is interrupted if the liquid level in the reservoir reaches the minimum threshold.

According to one embodiment, the delivery rate at which the condensed phase is pumped is increased if the liquid level in the reservoir reaches the minimum threshold.

The present invention makes it possible to overcome the disadvantages of the prior art. More particularly it provides an electricity production system relying on a Rankine cycle that is capable of operating with an organic heat-transfer fluid, in which the expansion member is protected from any damage in a way that is simple and economic.

This is achieved by virtue of the use of a liquid – vapor separator provided with a liquid reservoir, at the outlet of the evaporator, which is coupled to a control device capable of controlling the level of liquid in the reservoir.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1 schematically depicts a Rankine cycle that can be used to implement the invention.

Figures 2 to 5 schematically depict part of a system according to one embodiment of the invention, in various phases of operation.

DESCRIPTION OF EMBODIMENTS OF THE INVENTION

The invention is now described in greater detail and nonlimitingly in the description which follows.

Referring to **figure 1**, an electricity production system according to the invention relies on a Rankine cycle comprising an evaporator 1, an expansion member 2, a condenser 3 and a circulation pump 4.

The Rankine cycle contains a heat-transfer fluid which is preferably an organic compound, for example a hydrocarbon, or a hydrofluorocarbon, or a hydrofluoroolefin, or a mixture of several such compounds.

Preferred compounds are HFC-134a (1,1,1,2-tetrafluoroethane), HFC-32 (difluoromethane), HFC-125 (pentafluoroethane), HFC-152a (1,1-difluoroethane), HFC-134 (1,1,2,2-tetrafluoroethane), HFC-161 (fluoroethane), HFO-1234yf (2,3,3,3-tetrafluoropropene), HFO-1234ze (1,3,3,3-tetrafluoropropene), HFO-1233zd (1-chloro-3,3,3-trifluoropropene), HFO-1336mzz (1,1,1,4,4,4-hexafluorobutene) in E or Z form, HC-600 (butane), HC-600a (2-methylpropane) and HC-290 (propane).

The evaporator 1 is coupled to a heat source.

A generator 5 is coupled to the expansion member 2. It provides electrical current as an output from the system.

The heat-transfer fluid receives heat from the heat source in the evaporator 1. It is thus heated, evaporated and possibly superheated. The energy thus accumulated in the fluid is restored as mechanical work by expanding the fluid in the expansion member 2. This mechanical work is itself converted into electrical current in the generator 5 in the way known per se.

The expanded heat-transfer fluid is condensed in the condenser 3 then returned to the evaporator 1 by means of a pump 4.

Although just one element in each category has been depicted in **figure 1**, it is possible to provide several of such elements, for example several evaporators and/or several expansion members and/or several pumps and/or several condensers, these being either in series and/or in parallel.

The term “*evaporator*” is used here in its generally accepted meaning. It denotes a heat exchanger designed to heat, evaporate and possibly superheat the fluid. The evaporator may therefore include different sections, for example a heating section, a vaporizing section, and possibly a superheating section. It may be or include a boiler.

It is possible by way of heat source to use for example a source of hot liquid (a geothermal source), an industrial stream (combustion gas for example) or even another thermal facility (cooling or air conditioning plant, combustion engine, etc.) to which the system of the invention can be coupled.

The heat source may either exchange heat directly with the heat-transfer fluid in the evaporator 1 or exchange heat therewith by means of an intermediate heat-transfer-fluid circuit.

Likewise, within the condenser 3, the heat-transfer fluid transfers heat to a cold source which may, for example, be air or water from the surroundings, either directly or by means of an intermediate heat-transfer-fluid circuit.

The expansion member 2 is preferably a turbine, notably a centrifugal, screw-type, piston-type or rotary (scroll type) turbine.

With reference to **figures 2 to 5**, the invention provides a liquid – vapor separation device 6 between the evaporator 1 and the expansion member 2. This device allows the heated and evaporated (and possibly superheated) fluid to be separated into a vapor phase (which in theory is the predominant or very widely predominant proportion) and a possible liquid phase. The liquid phase is collected in a reservoir 12 where it accumulates.

For preference, the liquid– vapor separator 6 simply comprises the reservoir 12, a dip tube connected to the outlet of the evaporator 1 dipping into

the liquid contained in the reservoir 12, and a gas outlet connected to the inlet of the expansion member 2 arranged toward the top of the reservoir 12.

Alternatively, the liquid – vapor separator 6 may comprise a cyclone or a coalescence membrane or any other separation device, the reservoir 12 then
5 being intended to collect the previously separated liquid phase.

In the embodiment illustrated, a liquid recirculation line 9 is connected to the outlet of the reservoir 12; it is advantageously fitted with a valve 10. The liquid recirculation line 9 may notably feed into the evaporator 1. For example, it may be connected to a pipe 7 situated between the pump 4 and the
10 evaporator 1. Alternatively, the pipe 7 may feed into the evaporator 1 directly, at its inlet or some intermediate point.

Alternatively, the liquid recirculation line 9 may be connected between the expansion member 2 and the condenser 3, or between the condenser 3 and the pump 4.

15 In the embodiment illustrated, one or more liquid level sensors are provided in the reservoir 12 to detect when the liquid level reaches a maximum liquid threshold 13 and a minimum liquid threshold 14 in the reservoir 12. These liquid level sensors are connected to a control device 15.

For preference, the maximum liquid level 13 is situated below the upper
20 end of the reservoir 12, and the minimum liquid threshold 14 is situated above the lower end of the reservoir 12 – in order to prevent the possibility of the reservoir 12 becoming completely empty or completely full.

The control device 15 advantageously controls the valve 10 and the pump 4.

25 The control device 15 empties the reservoir 12 if the liquid level in the reservoir reaches the maximum threshold 13. That makes it possible to avoid any risk of liquid being drawn into the expansion member 2.

The term “*emptying*” means the action involving complete or partial emptying of the liquid reservoir 12. For preference, the emptying is only partial.

30 The emptying of the reservoir is performed by opening the valve 10. If the reservoir 12 is situated above the evaporator 1, the emptying of the reservoir can be accomplished simply under the effect of gravity. Alternatively, if necessary, it is possible to provide an additional pump on the liquid recirculation line 9 and controlled by the control device 15.

35 For preference, simultaneously with the opening of the valve 10, the control device 15 acts on the pump 4 in order to reduce the delivery rate thereof. Reduction in the delivery rate is performed down to a zero or non-zero

value. In the former instance, reducing the delivery rate means halting the stream of fluid through the pump 4. It must be appreciated that the same function may be performed by having the control device 15 control a valve situated upstream or downstream of the pump 4.

5 Conversely, the control device 15 is designed to put a stop to the emptying of the reservoir 12 if the liquid level in the reservoir reaches the minimum threshold 14, this being notably so as to ensure that the quantity of liquid in the reservoir 12 is sufficient for the liquid – vapor separator correctly to perform its function and so as to allow the system to return to its normal mode
10 of operation. The end of the emptying is performed by closing the valve 10. For preference, at the same time, the control device 15 acts on the pump 4 in order to increase the delivery rate thereof (which means to say to switch the pump 4 back on if it had previously been switched off).

15 **Figures 2 to 5** depict the system of the invention in various configurations.

 In **figure 2**, the pump 4 is pumping the liquid and the valve 10 is closed. The liquid level in the reservoir 12 is between the minimum level 14 and the maximum level 13. This liquid level has a tendency to rise over the course of time, as the liquid phase present at the evaporator outlet is gradually collected
20 in the liquid – vapor separator 6.

 In **figure 3**, the liquid level in the reservoir 12 reaches the maximum threshold 13. In response, the control device 15 stops the pump 4 (or reduces the delivery rate thereof to a non-zero value), and opens the valve 10.

 In **figure 4**, the liquid from the reservoir is emptied by the liquid
25 recirculation line 9 (for example under the effect of gravity). This liquid is heated, evaporated and, if appropriate, superheated, in the evaporator 1 so that the system continues to operate and to produce electrical current during this emptying phase. The liquid level in the reservoir 12 becomes lower during this emptying phase.

30 In **figure 5**, the liquid level in the reservoir 12 reaches the minimum level 14. In response, the control device 15 starts up the pump 4 (or increases the delivery rate thereof if this pump was not previously switched off) and closes the valve 10. The system thus returns to the state in **figure 2**.

 In place of an opening and closing of the valve 10 it is also possible to
35 provide a non-zero rate of flow of liquid in the liquid recirculation line 9 even outside of the emptying phases. In this case, the control device 15 makes it possible to increase the rate of flow in the liquid recirculation line 9 during the

emptying phases. This alternative form may prove beneficial when a significant proportion of liquid is present at the outlet of the evaporator 1.

The embodiment illustrated in **figures 2 to 5** offers the advantage of being particularly simple in design and implementation. However, it is also possible to provide a more complex system able to adapt more closely to the variations in the conditions of use, for example by providing other level thresholds in addition to the maximum threshold 13 and the minimum threshold 14, the control device 15 then being designed to regulate the delivery rate of the pump 4 and/or the rate at which the liquid from the reservoir 12 is recirculated according to the level of liquid in the reservoir 12.

CLAIMS

- 5 **1.** A system for producing electricity, comprising a closed heat-transfer-fluid circuit which comprises an evaporator (1), an expansion member (2), a condenser (3) and a circulation pump (4), a generator (5) being coupled to the expansion member (2), in which a liquid – vapor separator (6) provided with a liquid reservoir (12) is placed between the evaporator (1) and the expansion member (2), the system being further provided with a control device (15) configured to empty the reservoir (12) if the liquid level in the reservoir reaches a maximum threshold (13).
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- 15 **2.** The system as claimed in claim 1, in which the heat-transfer fluid is organic.
- 20 **3.** The system as claimed in claim 1 or 2, in which the emptying of the reservoir (12) is performed by a liquid recirculation line (9) feeding into the evaporator (1).
- 25 **4.** The system as claimed in one of claims 1 to 3, in which the control device (15) is configured to reduce the delivery rate of the circulation pump (4) if the liquid level in the reservoir reaches the maximum threshold (13).
- 30 **5.** The system as claimed in one of claims 1 to 4, in which the liquid level in the reservoir (12) is kept between a minimum threshold (14) and the maximum threshold (13).
- 35 **6.** The system as claimed in claim 5, in which the control device (15) is configured to put a stop to the emptying of the reservoir (12) if the liquid level in the reservoir reaches the minimum threshold (14).
- 7.** The system as claimed in claim 5 or 6, in which the control device (15) is configured to increase the delivery rate of the circulation pump (4) if the liquid level in the reservoir reaches the minimum threshold (14).

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8. A method for producing electricity, comprising the following concurrent steps:
 - heating and evaporating a heat-transfer fluid using a heat source;
 - separating the heat-transfer fluid that has undergone evaporation into a liquid phase and a vapor phase, the liquid phase being stored in a liquid reservoir;
 - expanding the vapor phase to allow the generation of an electrical current;
 - condensing the expanded vapor phase; and
 - pumping the condensed phase;and further comprising the following steps:
 - monitoring the liquid level in the liquid reservoir; and
 - emptying the liquid reservoir when the liquid level in this reservoir reaches a maximum threshold.
 9. The method as claimed in claim 8, in which the heat-transfer fluid is organic.
 10. The method as claimed in claim 8 or 9, in which the emptied liquid is recirculated to the heating and evaporation step.
 11. The method as claimed in one of claims 8 to 10, in which the delivery rate at which the condensed phase is pumped is reduced when the liquid level in this reservoir reaches the maximum threshold.
 12. The method as claimed in one of claims 8 to 11, in which the liquid level in the reservoir is constantly kept between a minimum threshold and the maximum threshold.
 13. The method as claimed in claim 12, in which the step of emptying the reservoir is interrupted if the liquid level in the reservoir reaches the minimum threshold.

14. The method as claimed in claim 12 or 13, in which the delivery rate at which the condensed phase is pumped is increased if the liquid level in the reservoir reaches the minimum threshold.