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Modelling and experimentation of heat exchangers for Ocean Thermal Energy Conversion during transient operation

Alexandre Dijoux[a,b,*], Frantz Sinama[a], Olivier Marc[a], Jean Castaing-Lasvignottes[a]

[a]*PIMENT Laboratory, University of Reunion Island, 40 avenue de Soweto 97410 Saint-Pierre, Reunion Island, France*
[b]*NAVAL Energies, Indret 44620 La Montagne, France*

Abstract

Ocean Thermal Energy Conversion (OTEC) is considered as a non-intermittent base energy resource. It consists in using the difference of temperature between the hot surface seawater in tropical seas and the cold deep seawater to produce electricity by mean of a thermodynamic motor cycle. The Organic Rankine Cycle (ORC) is adapted for this kind of application. In the literature, performances of such a system are often studied under steady state conditions, mainly because the temperature of the sources do not present intermittency. However, the study of the transient behavior of an OTEC power plant could be of major interest for piloting purposes. With this aim, a dynamic model of heat exchanger is presented with the use of a Moving Boundary Model (MBM) in order to distinguish the monophasic and diphasic parts of the transfer. Moreover, experiments have been carried out on an onshore OTEC prototype located in Reunion Island and compared to simulations. The case being studied is an increase of 1 °C of the hot water during 3 minutes leading to a good agreement between simulation and measurement.

Keywords: Ocean Thermal Energy Conversion (OTEC); Organic Rankine Cycle (ORC); heat exchangers; Moving Boundary Model (MBM); dynamic modelling

* Corresponding author. Tel.: +33650-69-04-85; fax: +262-2-62-57-95-51.
E-mail address: alexandre.dijoux@univ-reunion.fr

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1. Introduction

Producing electricity in a durable way has become in recent decades a necessity to respond to the need of the populations. This fact is particularly important in islands territories, where the electric grid cannot be interconnected with other grids. In Reunion Island, a French overseas territory located near Mauritius and Madagascar in the Indian Ocean, the energy demand per person as well as the population has been increasing during recent years. To supply the energy demand, Reunion Island is dependent on coal and fuel importation. To overcome this situation, investments are made in order to develop the use of renewable energy in order to rise the energy autonomy [1]. Today, about 36 % of the electricity produced in Reunion Island come from renewable energy. However, the massive use of intermittent energies such as photovoltaic causes instabilities into the grid. Therefore, the use of intermittent renewable energy is limited [1] and new projects have to integrate a storage unit. Hence, Ocean Thermal Energy Conversion (OTEC), which is a non-intermittent renewable energy resource, appears to be a good opportunity for territories with non-interconnected grid as Reunion Island.

On one hand, the surface seawater stores the energy of the sun and is at a constant hot temperature during day and night (in Reunion Island 28 °C in summer and 23 °C in winter). On the other hand, the deep seawater is cold (about 5 °C at 1000 m depth) and easily accessible close to the coast. OTEC consists in using this temperature difference as an energy resource to produce electricity. One reliable way to do it is the Organic Rankine Cycle (ORC) [2,3]. As the source temperatures are constant at a one day time scale, most of the studies carried out about the ORC applied to OTEC consider steady state behavior of the cycle [4–8]. However, the transient response of such a system can be of major interest to evaluate the controllability of a power plant. Bai *et al.* [9] developed a dynamic model for an OTEC power plan using the Uehara cycle instead of the ORC. Heat exchangers were considered as single zone and global heat transfer coefficients were taken constant, so their model is adapted only for small mass flow rate and power variations. Sinama *et al.* [3,10] also carried out research about the dynamic modelling of OTEC by using the equivalent Gibbs system method. Again, global heat transfer coefficients are considered constant and the model is only applicable near the nominal point of operation.

Other studies focus on the dynamic modelling of ORC applied to other thermal sources (such as waste heat recovery, geothermic or solar heat) [11–15]. It is generally admitted that heat exchangers drive the dynamic response of a power plant, because response times of pumps and turbine are negligible. The behavior of heat exchangers can be determined by using a single zone model, a spatial discretization method or a Moving Boundary Model (MBM). Wei *et al.* [12] conducted a comparison between a discretization method and a MBM. They concluded that the latter shows results similar than those obtained by the discretization method but with a lower number of zones and thus a smaller computational time.

In this paper, a dynamic model of the evaporator of an OTEC power plant is presented by using a MBM method. Simulations are then conducted are compared to measurements done in the OTEC onshore prototype located in Reunion Island to evaluate the accuracy of the model.

Nomenclature

A	section of the flow (m^2)	z	coordinate along the heat exchanger (m)
c_p	heat capacity ($J.kg^{-1}.K^{-1}$)	*Greek symbols*	
h	specific enthalpy ($J.kg^{-1}$)	α	heat transfer coefficient ($W.m^{-2}.K^{-1}$)
L	length (m)	γ	mean vapour quality (-)
$\dot{m}$	mass flow rate ($kg.s^{-1}$)	ρ	volumic mass ($kg.m^{-3}$)
S	heat exchange surface (m^2)	*Indices and exponent*	
P	pressure (Pa)	in	inlet
$\dot{Q}$	thermal power (W)	out	outlet
$\dot{q}$	thermal power per unit of length ($W.m^{-1}$)	hsw	hot seawater
T	temperature (K)	w	wall
t	time (s)	wf	working fluid
$\dot{W}$	mechanical power (W)	sat	saturation

2. Description of the heat exchanger model

In an ORC, heat exchangers (evaporator and condenser) drive the dynamic response of the machine. In the evaporator, the working fluid enters in a subcooled liquid state (1), is heated to saturation, evaporates (2), and finally the vapor may be overheated (3), as shown in Fig. 1. The heat exchange can thus be divided into three parts: preheating, evaporation and overheating. This statement is the foundation of MBM (Moving Boundary Model). This three parts are distinguished, mainly because the heat transfer coefficient is generally different in a monophasic zone and in a diphasic zone. In the condenser, the three parts are desuperheating, condensation and subcooling. The method is the same for both heat exchanger. Thus, for clarity reasons, only the evaporator will be described in the following.

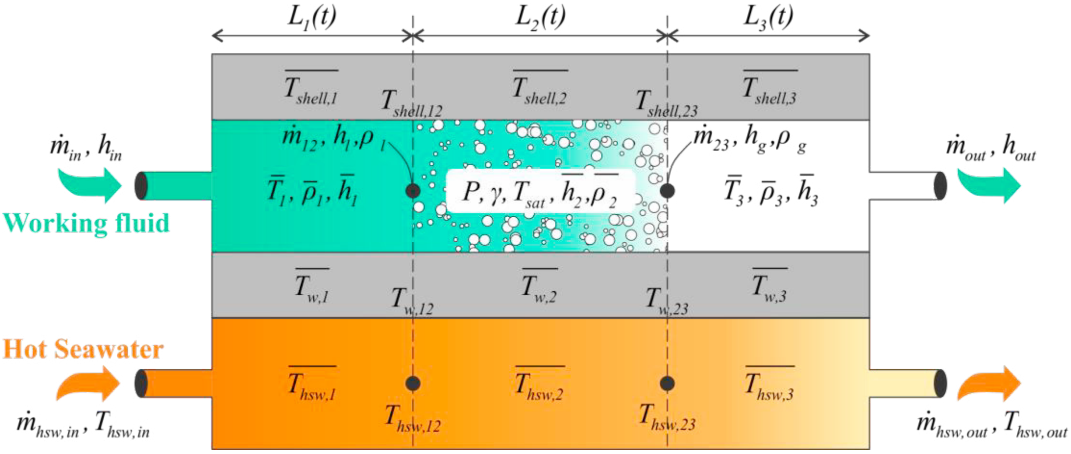

Fig. 1. Schematic representation of the three zones of MBM for the evaporator of an OTEC power plant and nomenclature of variables

Four media are taken into account: two fluid media (water and working fluid), and two solid media (the wall between the two fluid and the shell). Below are given the one dimensional local mass and energy conservation equations for the fluids:

$$\frac{\partial A\rho}{\partial t} + \frac{\partial \dot{m}}{\partial z} = 0 \tag{1}$$

$$\frac{\partial (A\rho h - AP)}{\partial t} + \frac{\partial \dot{m}h}{\partial z} = \dot{q} \tag{2}$$

Where A is a mean section of the flow, in m^2, taken as the ratio of the volume to the length. $\dot{q}$ is the heat power per unit length, it could be written as $\dot{q} = \partial \dot{Q} / \partial z$.

The method consists in integrating the conservation equations over the three zones. For the preheating zone, an integration is made between $z = 0$ and $z = L_1(t)$, for the evaporation zone between $z = L_1(t)$ and $z = L_1(t) + L_2(t)$ and for the overheating zone between $z = L_1(t) + L_2(t)$ and $z = L$, by using the Leibniz's rules for differentiation of integrals with time dependent bounds. Details of a such development are given in [16]. Pressure drops are neglected and the pressure is assumed to be constant along the heat exchanger. Moreover, heat losses are neglected as well. In the solid media, an energy conservation equation is also integrated in each zone. In the end, a set of 18 differential equations with 18 time dependent variables is obtained. In each zone, the amount of heat exchanged is determined by:

$$\forall i \in [\![1;3]\!], \quad \begin{cases} from\ wall\ to\ working\ fluid: \dot{Q}_{w-wf,i} = \alpha_{w-wf,i} S_i (\overline{T_i} - \overline{T_{w,i}}) \\ from\ hot\ seawater\ to\ wall: \dot{Q}_{hsw-w,i} = \alpha_{hsw-w,i} S_i (\overline{T_{hsw,i}} - \overline{T_{w,i}}) \\ from\ working\ fluid\ to\ shell: \dot{Q}_{wf-shell,i} = \alpha_{wf-shell,i} S_{shell,i} (\overline{T_{wf,i}} - \overline{T_{shell,i}}) \end{cases} \tag{3}$$

With:

$$\alpha_{w-wf,i} = \frac{1}{\frac{R_w S_i}{2} + \frac{1}{\alpha_{wf,i}}} \quad (4) \qquad \alpha_{hsw-w,i} = \frac{1}{\frac{R_w S_i}{2} + \frac{1}{\alpha_{hsw,i}}} \quad (5)$$

Where R_w is the thermal resistance of the wall. Heat transfer coefficient in fluids side $\alpha_{wf,i}$ and $\alpha_{hsw,i}$ are determined by correlations [17–19] that were the best concordant with measurement in steady state in the OTEC onshore prototype in Reunion Island, according to the work of Castaing-Lasvignottes *et al.* [20,21].

3. Description of the OTEC onshore prototype

An OTEC onshore prototype was designed and built by NAVAL Energies (ex-DCNS), with co-funding from Region Reunion. The aim of this prototype is to test performances of heat exchangers in real conditions of operation of an OTEC system. The heat exchange power in the design point of operation is 500 kW [22]. Hot water and fresh water at temperatures equal to those of surface and deep seawater are provided by a heat pump via two water loop, as shown in Fig. 2. The equivalent electricity production of this system is about 15 kW, but the turbine is replaced by a pseudo-turbine that reproduce an equivalent thermodynamic transformation without producing power [21]. In this study, the evaporator used is a flooded shell and tube one, with smooth tubes. The condenser is also a shell and tube heat exchanger. The working fluid is ammonia.

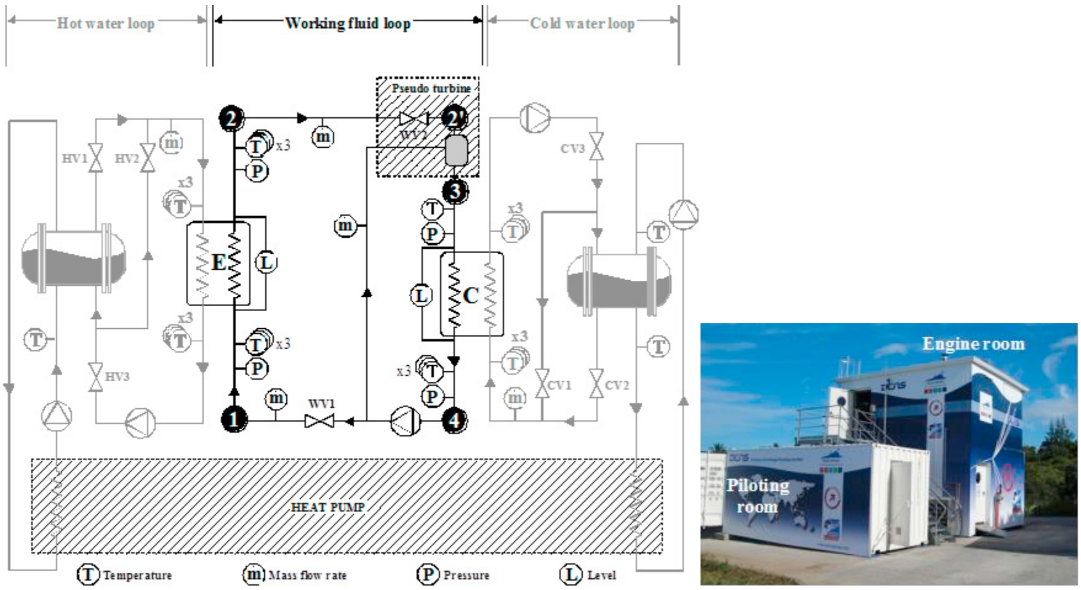

Fig. 2. Global schematic diagram and photography of the OTEC experimental installation in Reunion Island [22].

4. Results and discussion

The presented model with MBM is used to simulate the behavior of the OTEC onshore prototype during an increase of inlet hot water temperature (from 27°C to 28.5 °C). Input values for the simulation are the temperature and mass flow rate of inlet hot water $T_{hsw,in}(t)$ and $\dot{m}_{hsw,in}(t)$ as well as the ammonia vapor mass flow rate $\dot{m}_{out}(t)$. The mass flow rate of water is 45 kg/s and that of ammonia is 0.32 kg/s. The inlet ammonia mass flow rate is assumed to be the same at the outlet. The ammonia inlet temperature in the evaporator is 12.43 °C. Properties of ammonia and water are obtained thanks to the Coolprop data base [23]. The surface exchange of the evaporator is 66 m^2. This latter holds in 0.435 m^3 of water and 0.350 m^3 of ammonia. Tubes are made of titanium (204 kg), and the shell of steel (1471 kg). The mean heat exchange coefficient on the water side is about 5600 $W.m^{-2}.K^{-1}$. On the ammonia side, it is 124 $W.m^{-}$

^{2}.K^{-1} on the preheating zone, approximately 2600 W.m^{-2}.K^{-1} in the evaporation zone and about 20 W.m^{-2}.K^{-1} in the overheating zone. The length of each zone do not presents important variations, even if the length of the evaporating zone is slightly decreasing from 67 % to 64 % of the overall length.

The comparison between the simulation result and measurements is given in Fig. 3. Results show that the prediction is always inside the uncertainty interval. In particular, there is no phase displacement between simulation and measurement. The RMSE (Root Mean Square Error) for the heat power is $\Delta\dot{Q} = 10.7\ kW$, that represents 2.6 % of the mean heat power. Moreover, it can be noticed that the time response of the system is relatively short: the maximum of the output water temperature is reached 10 s after the maximum of the input water temperature. And for the pressure in the ammonia side, the maximum is reached with a delay of just 9 s. This fact supports that the water in the heat exchanger constitutes the major part of the thermal inertia of the heat exchanger.

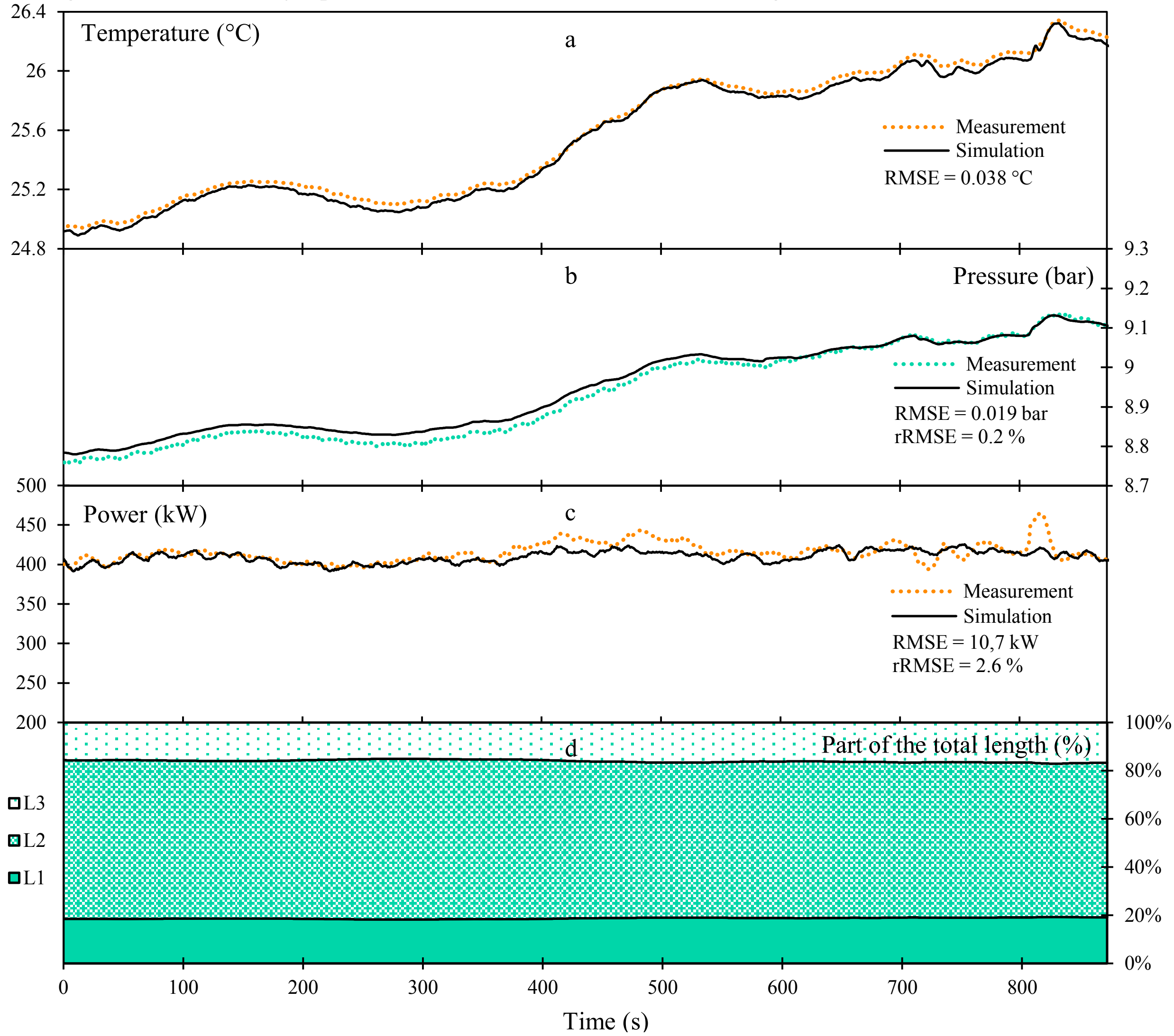

Fig. 3. Comparison between simulation outlet and measurement. a) Outlet temperature of hot water. b) Ammonia pressure in the evaporator. c) Heat exchanged on the water side d) Relative size of the three zones of the evaporator

5. Conclusion

In this study, a dynamic model of heat exchanger for an ORC applied to OTEC is presented. A moving boundary model (MBM) is used and takes into account the size variation of the different phase of heat transfer (preheating, evaporation and overheating for the evaporator). A simulation of an OTEC onshore prototype located in Reunion Island is then computed. Results show quite good agreement with measurement, as the predicted value is always inside the uncertainty interval. Correlations used to determine heat transfer coefficients had already been validated in steady state in a previous work [20]. It is here established than this correlations can also be used during transient in the operating conditions presented. This results will be useful to evaluate the controllability of an OTEC power plant. This work is in progress at the moment.

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