International Journal of Heat and Mass Transfer 85 (2015) 88–97

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Simulation and verification of a non-equilibrium thermodynamic model for a steam catapult's steam accumulator

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ARTICLE INFO

*Article history:*
Received 8 March 2014
Received in revised form 23 January 2015
Accepted 24 January 2015

*Keywords:*
Steam catapult's steam accumulator
Non-equilibrium thermodynamic model
Non-equilibrium thermodynamic process

ABSTRACT

A non-equilibrium thermodynamic model for a steam catapult's steam accumulator is established based on the mass and energy conservation of steam and water by introducing an evaporation (condensation) relaxation time. The accuracy of the model is validated through testing with a lab-based steam accumulator system, which is also used to determine the key coefficients for the mathematical model. The influence of key parameters on the charging performance of the steam accumulator is investigated using potential theory and a mechanism analysis of the non-equilibrium thermodynamic process of the steam accumulator. The results show that the charging time decreases as the charging energy per unit time increases, meanwhile the pressure drop ratio caused by the non-equilibrium thermodynamic process increases as increase of the charging energy per unit time. Furthermore, the main driving force of the macroscopic non-equilibrium thermodynamic process of a steam accumulator is the energy potential difference between the current and the saturated state, increasing the water filling coefficient of the steam accumulator improves its energy storage, but has a negative impact on the cycle time of the system. Finally, the charged steam flow has a stronger influence on the water temperature distribution of the steam catapult's steam accumulator than the steam enthalpy, and plays a leading role when the charging energy per unit time is constant.



## 1. Introduction

An essential part of an aircraft carrier's steam catapult, the steam accumulator provides the required amount and pressure of saturated steam for the steam catapult system in very short timeframe, and guarantees that the aircraft acquires the required take-off speed within the relatively short deck of an aircraft carrier. The steam accumulator of a steam catapult not only alleviates the impact of load disturbance on the boiler [1,2], but also greatly minimizes the required capacity of the boiler and so improves the maneuverability of the aircraft carrier. A steam catapult's steam accumulator is similar in terms of energy storage to general industrial wet-steam accumulator systems [3–6]. However, because the cycle of a steam catapult is only about 40 s, steam accumulators for steam catapults differ from industrial wet-steam accumulators by having extremely short charge and discharge times and in providing a large instantaneous steam output.

It remains challenging to accurately predict and analyze the dynamic characteristics of steam catapult's steam accumulators because the process involves a series of complex problems: flash evaporation, vapor liquid two-phase flow and various forms of heat transfer during the charging and discharging processes. Herein the emphasis and difficulty of simulation and performance research is to build the accurate mathematical model of steam accumulator. The fact that steam catapult systems drive an aircraft of more than 20 tons to take-off speeds instantaneously makes the working process of the catapult's steam accumulator show strong non-equilibrium thermodynamic characteristics. Therefore, it is important to investigate a non-equilibrium thermodynamic model to describe such a steam accumulator and its performance in order to ensure the efficiency, safety and stabilization of the steam catapult system. Currently, only American aircraft carriers have mastered steam catapult technology, so there are few papers about the non-equilibrium thermodynamic properties of steam catapult's steam accumulators due to technology publication restrictions concerning such military technology.

At present, most of the published dynamic mathematical models for steam accumulators have been established based on the lumped parameter method. With this method, researchers can simplify such dynamic models to aid in their study for different purposes. Yang et al. [7] described a discharge mathematical model of steam accumulator based on the assumption that the steam and

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.01.120
0017-9310/

**Nomenclature**

| | |
|---|---|
| $a$ | steam–water interface area concentration [$m^2/m^3$] |
| $A$ | valve admittance |
| $h$ | specific enthalpy [J/kg] |
| $H$ | enthalpy [J] |
| $L$ | water level [m] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $M$ | mass [kg] |
| $O$ | valve opening |
| $p$ | pressure [Pa] |
| $\Delta P$ | differential pressure [Pa] |
| $r$ | latent heat of evaporation [J/kg] |
| $R$ | radius [m] |
| $T$ | temperature [°C] |
| $v$ | specific volume [$m^3$/kg] |
| $V$ | volume [$m^3$] |
| $\alpha$ | heat transfer coefficient [W/($m^2$ K)] |
| $\tau$ | relaxation time [s] |

*Subscripts*

| | |
|---|---|
| 1 | water |
| 2 | steam |
| 21 | steam to water |
| B | boundary |
| c | condensation |
| e | evaporation |
| in | inlet |
| out | outlet |
| pt | phase transfer |

*Superscripts*

| | |
|---|---|
| $'$ | saturated water |
| $''$ | saturated steam |

water in the steam accumulator are still isothermal and saturated, and that the physical parameters of both the steam and the water always change along with the pressure. Steinmann and Eck [8] established a steam accumulator equilibrium model to calculate the discharged steam mass. The various physical parameters in the model were determined by using the average of the beginning and end state values of the discharge. Baldini et al. [9] studied the steam accumulator of a solar thermal power system. The steam accumulator was assumed to be adiabatic, where the steam mass was ignored and the temperature inside the steam accumulator was uniform distribution. Due to the type of system, the steam accumulator was heated by a solar collector rather than by charged steam, and the water came from the condenser. Thus, the conservation equations of the steam accumulator combined with the assumption of an equilibrium model were relatively simple. Shnaider et al. [10] developed a dynamic mathematical model for the charging process of a steam accumulator which assumed that the saturated steam state was described by the ideal gas law, the steam accumulator was kept saturated and at equilibrium, and the temperature and the physical parameters of the working medium were a function of the pressure. Bai et al. [11] described a mathematical model under two conditions, one that considered that the pressure of the steam accumulator changed linearly during the discharging process, while the other assumed that the discharged steam flow was constant and so the pressure changed accordingly. Li et al. [12] fit the differential expression for the evaporation rate of a steam accumulator used in a solar power tower system of 1 MW. Ershu et al. [13,14] assumed the entire process—the heat transfer between steam and water, the condensation of the steam through the phase interface and the flash evaporation of the saturated water—finished instantly and so there was no relaxation time between phase changes. Thus, the mass and energy conservation equations for both steam and water were built by introducing dynamic evaporation of the water and condensation of the steam to carry out the mass and energy transfer between the steam and water in the steam accumulator of a solar power tower plant. Jin et al. [15–18] developed a steam accumulator charging model that included the steam source device and a steam regulating valve on the basis of variable mass thermodynamics. The group showed a dynamic change in the pressure in the steam accumulator during the charging process by considering the interacting influences among the devices.

Stevanovic et al. [19] from Serbia proposed a non-equilibrium dynamic model in 2012, where the mass and energy conservation equations for both steam and water considered the phase change process of the working medium was established so as to investigate dynamic change trends in parameters such as pressure and water level.

In summary, virtually almost all of the mathematical models for steam accumulators previously established by researchers are based on the equilibrium thermodynamic assumption. The equilibrium model assumes that the water and steam are saturated and that all steam condensation and water flash evaporation processes are instantaneous, although a substantial deviation could exist in the accumulator during rapid charging or discharging. These models ignore the phenomenon where subcooled water and superheated steam may exist during charging and discharging. Due to the thermal and mass inertia of the liquid, there will be a delay for phase change, however, the influence of non-equilibrium thermodynamic processes caused by the relaxation time on the dynamics of a steam accumulator has not been taken into account. Meanwhile many previous mathematical models are established only for a single charging or a discharging process, the generality of the model is not enough. The previous models are short of experimental verification or the working condition of the verification is too single, the accuracy of the model is unconvincing. In addition, the previous works lack of mechanism analysis of the non-equilibrium thermodynamic process of the steam accumulator and the influence research of some key parameters on charging performance of the steam catapult's steam accumulator.

In order to overcome the drawbacks of the previous models, the mass and energy non-equilibrium thermodynamic models for water and steam are built separately according to the operating characteristics of steam accumulators used for steam catapults in this work. The models based on the non-equilibrium thermodynamic are used to calculate the water and the steam thermodynamic parameters separately, which might have different temperatures although the two phases are in contact. The model introduces an evaporation (condensation) relaxation time, which implies the evaporation and condensation rates are finite and provides more accurate predictions of the steam accumulator pressure, temperature and enthalpy during charging and discharging process. We validate the accuracy of this mathematical model using experimental data of different working conditions obtained from a laboratory-based steam accumulator system, which also confirms the key coefficients (evaporation and condensation relaxation time) of the model. We then examine the influence of some key parameters on charging performance of the steam catapult's