早稲田大学大学院理工学研究科

博 士 論 文 概 要

論 文 題 目

A Study on The Dynamic Characteristics and Control
of Heat Exchangers in Waste Heat Recovery Systems

廃熱回収設備に用いられる熱交換器の

動的挙動と制御に関する研究

申 請 者

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Heat exchangers are used extensively in various industrial process, such as power plants and so forth. With the evolution of many processes, precise and fast operations for start up, shutdown, emergency situation and load changes are required. The traditional design based on the steady state data becomes inadequate, and attention has been focussed on investigating the dynamic characteristics of the heat exchangers in order to perform the most appropriate control, design and operation.

Previous research works are concerned with the dynamic behavior of several types of a single heat exchanger, especially shell and tube heat exchangers. In practice, some connection systems of heat exchangers are frequently encountered, for example the two series-combined heat exchangers used for waste heat recovery. Their dynamic characteristics were firstly investigated by S.Kawai and T.Machiyama, using the characteristics representation method. However, this method can not be used for simulating any thermal systems consisting of the heat exchangers or for control system design. As a result, simple lumped-parameter models with low order approximation are required for the simulation and optimal control design of the mentioned systems. In addition, no research works have been reported yet concerning the development of the simple lumped-parameter models for investigating the dynamic behaviors of the two series-combined heat exchangers. As a consequence, the first objective of this research work, as described in Chapter 1, is to develop lumped-parameter models for investigating a relation between the dynamic characteristics and control of the two series-combined heat exchangers and their static characteristics, subject to flow rate changes of the inside tube fluid.

In contrast to the conventional heat exchangers, moving-bed heat exchangers have received much less attention. A model for investigating the static characteristics of the moving-bed heat exchangers, with small particles and take into account the heat conduction effect within the particles, was firstly proposed by W.D. Munro and N.R. Amundson. However, this model is not general and can not be used for the heat exchangers with large particles. Furthermore, the heat conduction effect is actually negligible for the heat exchangers with small particles. In practice, there are some moving-bed heat exchangers, with very large particles and employed in waste heat recovery systems. For instance, the particle diameters of the heat exchangers of the waste heat recovery system in sinter cooler are some 200 mm. In addition, no research works have been reported yet concerning the investigation on their static and dynamic characteristics. As a consequence, the second objective of this research work is to develop a model of the moving-bed heat exchangers, with large particles and taking into account the heat conduction effect, for investigating their static and dynamic characteristics, as also described in Chapter 1. Particularly, parameters having effect on their static and dynamic characteristics are investigated.

Fundamental dynamic equations of the two series-combined heat exchangers are firstly derived in Chapter 2. They are subsequently converted into lumped-parameter models by the method of weighted residuals(MWR). Their static equations are also derived for establishing original charts which can be used for determining the transient response types of the heat exchangers.

In Chapter 3, fundamental equations of the moving-bed heat exchangers, with large particles and taking into account the heat conduction effect, are derived. They are subsequently converted into dimensionless models. In addition, parameters governing the heat exchanger characteristics are defined, namely the number of transfer unit(NTU), the heat capacity rate ratio(Cr) and the Biot number(Bi).

The validity of the two series-combined heat exchangers was firstly verified by conducting some experiments of step and frequency responses subject to flow rate changes of the inside tube fluid in Chapter 4. It has been found that the MWR linearization model gives good approximation results for the case of flow rate changes of small amplitudes. For the case of flow rate changes of both large and small amplitudes, the MWR non linearization model gives good agreement with the experimental data. In addition, some experimental data of transient responses were presented to confirm the validity of the model of the moving-bed heat exchangers.

A correlation between the dynamic behaviors of the two series-combined heat exchangers and their static and structural characteristics, subject to flow rate changes of the inside tube fluid, have been investigated in Chapter 5 using the MWR lumped-parameter models with 2nd order approximation and based on their static and structural characteristics. It has been found that the transient response types, the reverse or non reverse responses, are dependent upon the static characteristics of not only the upstream heat exchanger but also the downstream heat exchanger. In other words, the transient response types are dependent upon the number of transfer unit of the upstream heat exchanger and the flow rate ratio of the downstream heat exchanger. The overshoot magnitude of the reverse response is also dependent upon the static and structural characteristics of the upstream and downstream heat exchangers. Furthermore, there is a correlation between the ratio of the number of transfer unit or the flow rate ratio of the downstream heat exchanger and the stability regions of the PI control system of the two series-combined heat exchangers.

Static and dynamic characteristics of the moving-bed heat exchangers are investigated in Chapter 6. It has been found that the heat conduction effect on the static behaviors of the heat exchangers, the heat exchanger effectiveness and the temperature distribution of the particle and gas along the moving-bed, is significant and has to take into account. The transient and frequency responses of the heat exchangers are mutually dependent upon three dimensionless parameters governing the characteristics of the heat exchangers(NTU, Cr and Bi). Moreover, it has been found that the heat conduction has a more significant effect on the static behavior than that on the dynamic characteristics.

Conclusions of this research work in Chapter 7 indicate that the proposed models of the two series-combined heat exchangers are practically appropriate not only for investigating their dynamic characteristics but also for designing their optimal control systems. In addition, the proposed model of the moving-bed heat exchangers can be used for designing any moving-bed heat exchangers and for designing their optimal control systems.