Design Optimization of Contra-rotating Axial Flow Pump with Rotational Speed Control for Effective Energy Saving

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論 文 名　: Design Optimization of Contra-rotating Axial Flow Pump with Rotational Speed Control for Effective Energy Saving
（効果的な省エネルギー化のための回転数制御を考慮した二重反転形軸流ポンプの設計最適化）

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論　文　内　容　の　要　旨

Compared with conventional high-specific-speed axial flow pumps, better cavitation performance and compact size have been achieved in contra-rotating axial flow pumps, where the rear rotor is additionally employed to the front rotor to convert the swirling flow kinetic energy to the pressure rise. Meanwhile, significantly deteriorated performance has also been observed in contra-rotating axial flow pumps at extreme off-design flow rates with design rotational speed. The reduced specific speed design of rear rotor has been found to be effective to improve the performance, whereas no explanation has been made in terms of internal flow physics including loss generation mechanism. Furthermore, the rotational speed control (RSC) of front and rear rotors has been experimentally proved to be effective to improve the performance at off-design flow rates. To further draw out this advantage of RSC in contra-rotating pumps, it seems to be important to take account of RSC into the rotor design. Since the pumps often operated not only at the design flow rate but in a wide flow rate range from deep part load to over load, the actual operation condition is to be also considered at the design stage of rotors to realize more effective energy saving. In this thesis, following issues (a)~(c) are investigated to establish the design method of contra-rotating axial flow pump with better energy saving performance:

(a) To understand the loss generation mechanism in rear rotor of contra-rotating axial flow pump by the appropriate method for the evaluation of location and quantity of loss generation.
(b) To construct a simple and robust performance prediction model to find the effective RSC method in contra-rotating axial flow pump. Then the proposed model is applied to find a solution for energy saving operations.
(c) To conduct the design optimization of rotors in contra-rotating axial flow pump with a performance prediction model and a genetic algorithm to obtain the best energy-saving solution with RSC.

The present thesis consists of the following five chapters.

In Chapter 1, the background and objective of the present study are introduced.

In Chapter 2, to investigate the mechanism of increased efficiency with the reduced specific speed design of rear rotor, three models with different specific-speed rear rotors are designed with the conventional method, and the flow fields are simulated by unsteady CFD (Computational Fluid Dynamics) simulation. To analyze the loss generation mechanism, two loss evaluation methods based on the entropy production rate and the material-derivative of rothalpy are employed. It is found that, although the both methods qualitatively estimate the local loss generation in the rear rotor, the derivative of rothalpy can give much better quantitative prediction of total amount of loss generation. Two distinct flow features are observed in the rear rotor, the corner separation at the hub corner of blades and the tip leakage vortex, both of which are responsible for the loss generation. With the evaluation of local loss generation based on the material derivative of rothalpy, the loss contribution of corner separation is found to be very small compared with that due to the tip leakage vortex. The tip leakage vortex in the higher specific speed rear rotor shows the strong interaction with the leading edge of adjacent blade, which seems to strengthen the flow blockage in the tip region. This is relieved in the lower specific speed rear rotor, resulting in the achievement of higher efficiency with it.

In Chapter 3, a fast and effective performance prediction model under RSC is established by considering the radial equilibrium condition, the conservations of rothalpy and mass, the empirical deviation angle, the blade-rows interaction and the empirical losses. Experimental and CFD results are employed to validate the proposed prediction model. It is found that the proposed model shows good enough accuracy in predicting performances of contra-rotating axial flow pump under RSC in the broad flow rate range. Furthermore, an energy saving application of the proposed model is also illustrated for two typical system resistances. Compared with the traditional valve control under the design rotational speed operation, the RSC method can well modify the pump head to satisfy the system resistance at wide flow rate range with the significantly improved energy performance.

In Chapter 4, to design the rotors under RSC with less computational cost while with good enough accuracy, the ANN (Artificial Neural Network) meta-models are constructed using the results of CFD simulations only at near-design flow rates with design rotational speed. To do so, sample designs are selected through DOE (Design of Experiment) with LHD (Latin Hypercube Design) under the limited number of design variables. Then, the performance prediction models are established by considering the radial equilibrium equation, the conservation equations of mass and rothalpy, the empirical deviation angle equation, the empirical equation including the meta-model toward the modification of theoretical head, the empirical cascade loss equation, the mixing loss equation, and the empirical other loss including the meta-model. By using the proposed models and the genetic algorithm (GA), design optimizations are conducted for the only rear rotor as well as for the both front and rear rotors. Compared with the CFD simulations, the performance prediction model for the rear rotor optimization shows good enough agreement in the results of total head, total efficiency and total Euler head, while the performance prediction model for optimization of front and rear rotors have about 10% discrepancies in the results of total head and total theoretical head at the extreme off-design flow rates. Such discrepancy seems to be the results of errors in both ANN’s prediction at over flow rates and the model calculation errors at low flow rates due to the occurrence of reversed flow which has been ignored in the models. As for the energy saving performance, the performance prediction model shows that, compared with the original rotors, the optimal design of front and rear rotor can consume less power to satisfy the systems resistance in a wide range of flow rate, where higher efficiency is kept. This fact indicates that the energy saving performance can be enhanced by considering RSC at the design stage of rotors in contra-rotating axial flow pumps. It can be easily made provided the prediction accuracy of the proposed model is further improved.

Chapter 5 is the conclusions of the present thesis.

〔作成要領〕

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