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Transient free convective heat transfer from co-rotating concentric disks

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Abstract—Experimental investigations are carried out for the determination of transient heat transfer coefficients between parallel co-rotating and concentrically stationary disks with internal heat generation. The experimental model simulates a typical induction motor with unequal losses in the stator and rotor at the start-up condition. The data collected cover a range of Taylor numbers for various heat inputs. Quantitative assessment is made for the increase in heat transfer with speed of rotation under free convective ambient conditions. Temperatures along the axial, radial and tangential directions are measured. Unsteady heat transfer coefficients to the ambient air are evaluated in the radially diverging section. The results of the corresponding R-C network are obtained on a digital computer. The predicted values of temperatures at the corresponding nodal points are compared with the measured values and found to be in good agreement. The results are potentially very useful in the thermal design of electrical machines, more specifically, radially ventilated induction motors.

INTRODUCTION

PREDICTION of the temperature distribution in an electrical machine, both for steady and unsteady state conditions, is a subject matter of great interest to researchers and engineers. It is essential to know the magnitudes of the highest temperatures and their locations and deviations from the average value because of their bearing on the design of the machines. The problem assumes greater complexity if one has to predict these values under transient conditions. The temperature distribution also depends upon the variation in type and location of the heat source, the ventilation system and the transient nature of rotor thermal loading.

The electrical analogue approach is one of the most commonly used methods for the prediction of temperature distribution for both steady and unsteady state conditions.

The need for transient analysis arises due to several electrical design factors such as reactive overload capacity, negative phase sequence, etc.

Several authors [1–3] reported work on heat transfer from disks with or without enclosure and for the case of parallel disks [4] without rotation. Mochizuki and Yang [5] reported work with co-rotating parallel disks but with steam as the heating fluid. To the authors' knowledge, no single paper has so far been reported for the determination of the heat transfer coefficient for the case of co-rotating parallel disks together with stationary concentric parallel disks, a configuration that closely resembles the rotor–stator of an electrical machine, with forced or free convection taking place between the disks. The present work aims at determining the heat transfer coefficients under free convective conditions.

SCOPE OF THE PRESENT WORK

A model of a stator and rotor of a typical induction motor with radial duct cooling is simulated. Typical loss distribution in the stator and rotor will be considered and simulated by heat sources at suitable locations. Even though there is forced flow of air, the present analysis is limited to the no-flow condition, i.e. free convection is predominant, with rotation of the rotor superimposed. This may simulate the condition of a fan failure wherein heat loads are to be met by self-ventilation. The heat transfer coefficients, obtained experimentally for different Taylor numbers and different heat losses in the stator and rotor, are used to calculate the convective resistances for the analytical model. The analytical model is solved for the transient and steady state temperature distributions for comparison with the measured values of temperatures.

DESCRIPTION OF EXPERIMENTAL SET-UP

The experimental set-up simulated the rotor and stator of a typical induction motor. It consisted of essentially four pairs of disks forming three radial ducts. Attention was paid to the central duct whereas the remaining two ducts on either side took care of the end effects. A sectional view of the test section is shown in Fig. 1. For simplicity the laminations of the motor are idealized to be a simple disk of solid steel. The disks were held in position by means of tie rods and end flanges which were suitably insulated to minimize axial conduction. The rotor was fixed to two end flanges with a hollow shaft through which thermocouples and power leads were taken out. To simulate the heat generation due to copper losses in

NOMENCLATURE

- A heat transfer area, $(2\pi N/4)(D_2^2 - D_1^2) + \pi NL(D_2 + D_1)$ [m²]
- B spacing between disks [m]
- D disk diameter: D_1, inner; D_2, outer; D_m, mean
- D_H hydraulic diameter, $2B$ [m]
- h average heat transfer coefficient [W m^{-2} K^{-1}]
- L axial dimension of disks [m]
- N number of disks
- n rotational speed of rotor [rps]
- Q heat input [W]
- T temperature [°C]
- Ta Taylor number, $B^2\Omega/\nu$.

Greek symbols
- ν kinematic viscosity of air [m² s^{-1}]
- Ω angular velocity of rotor, $2n$ rad s^{-1}.

Subscripts
- ∞ ambient
- av average
- R rotor
- S stator.

the conductor, rectangular heater elements each of 150 W capacity, were inserted into the slots made in the periphery of the rotor and stator disks. The stator assembly was similar and concentric with the rotor. After assembly the rotor–stator air gap was about 1 mm. Both rotor and stator surfaces were chrome-plated to prevent rust formation and maintain a clean surface. A power slip ring with brushes was used for power supply to the heating elements. Precautions were taken to prevent slipping and short circuiting of heating elements even at high rotational speeds. A variable speed drive was connected to the rotor shaft through a pulley mechanism for varying the speeds.

A number of copper–constantan thermocouples were fixed at different locations on the surface of the rotor and stator disks (complete details are given in ref. [6]). The experiments were carried out for different heat inputs and at various Taylor numbers. Temperatures in the axial, tangential and radial directions were measured to an accuracy of 0.1°C.

EXPERIMENTAL RESULTS AND DISCUSSION

The heat transfer performance for free convection through the radial ducts of the combined rotor–stator system with internal heat generation is expressed in terms of the average heat transfer coefficient h. Experiments were performed for rotor speeds of 0–700 rpm, which correspond to a Taylor number range of 0–102, where the Taylor number is defined as

$$Ta = B^2\Omega/\nu.$$

The air-side heat transfer coefficient is defined as

$$h = Q/A\Delta T$$

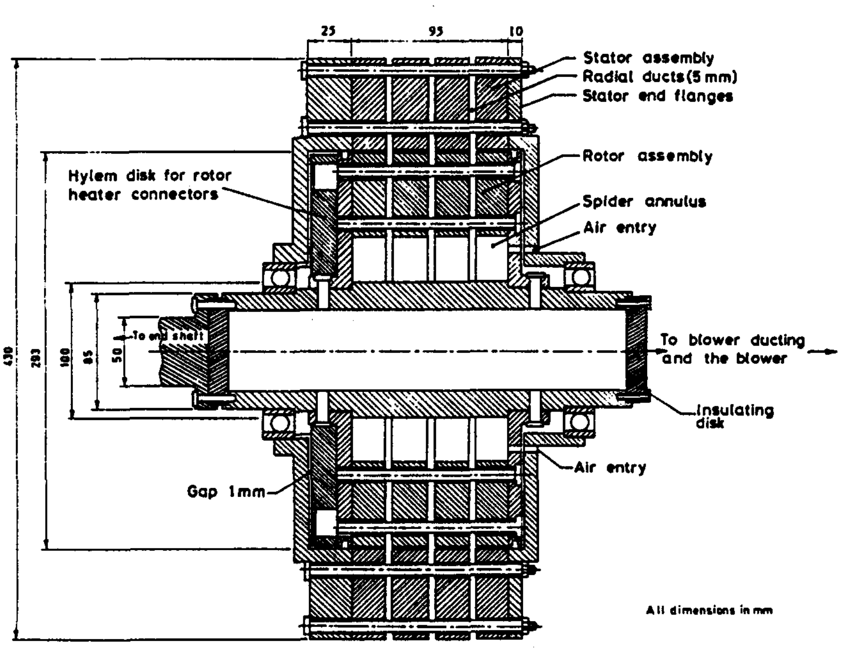

FIG. 1. Sectional view of the test section.

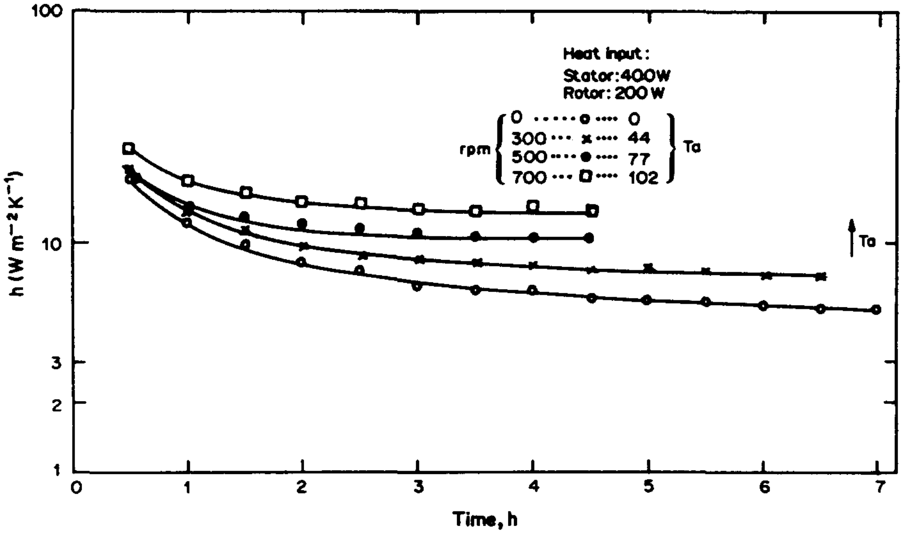

FIG. 2. Variation of HTC for stator radial duct with time.

where ΔT is the difference of average wall temperature and ambient temperature.

The variation of average transient heat transfer coefficient in the stator and rotor radial ducts is shown in Fig. 2 for different Taylor numbers. A similar trend was observed at various heat inputs. The graphs show a definite trend of increase in 'h' with increasing Ta. However, at each Ta, the heat transfer coefficient approaches a steady state value after a time period.

Transient temperatures were recorded every 30 min for each heat input and rotational speed until steady state was attained. However, it was noticed that the system took a considerable time to attain steady state due to large thermal inertia.

The heat transfer coefficient values are high initially and subsequently attain asymptotic values. The influence of rotation on heat transfer augmentation is very much evident and this is shown in terms of h_r/h_0 in Fig. 3.

Figures 4 and 5 show the absolute values of the heat transfer coefficients in both the stator and rotor radial ducts for different heating conditions. The values do not seem to depend much on the heat flux but are strong functions of Taylor number only.

A three-dimensional resistance–capacitance network was formulated for the two pairs of stator and rotor disks forming the central duct. The calculation of conductive resistances and capacitances poses no problem as they are dependent mainly on the thermophysical properties of the disk material. However, it is the convective resistance which relies heavily on the values of the heat transfer coefficients. The values of heat transfer coefficients obtained experimentally are made use of to calculate the convective resistances from the disks to the radial ducts and around all other convective zones. Assuming uniform heat flux, current injections to the nodes close to the heating elements were incorporated consistent with the heating of each lump representing a node. The network was solved on an IBM 370 computer using the software package SPICE with all the convective nodes grounded [7].

The values of temperature rise obtained analytically for a typical stator and a rotor node, when plotted against time, are shown in Fig. 6 and compared with the experimentally measured values shown in Fig. 7. The variation is about 10–20%, which may be considered as satisfactory. Similar trends are observed for other Taylor numbers and heat inputs.

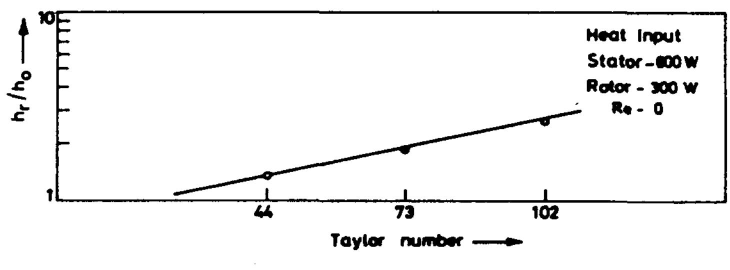

FIG. 3. Increase in heat transfer with rotation.

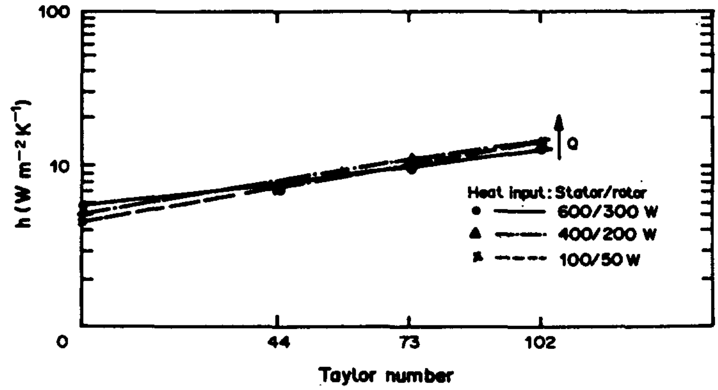

FIG. 4. Variation of HTC in stator radial duct.

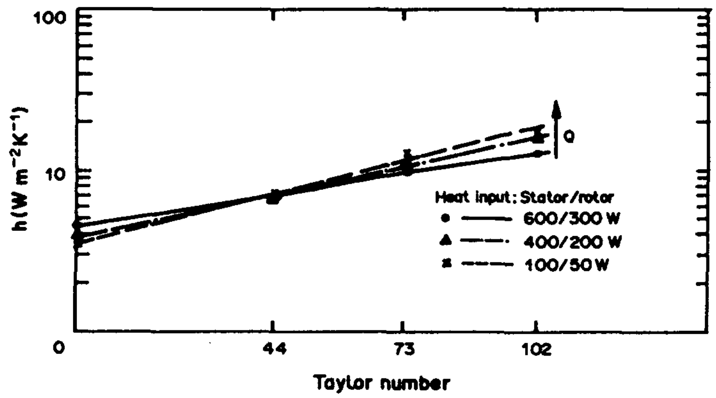

FIG. 5. Variation of HTC in rotor radial duct.

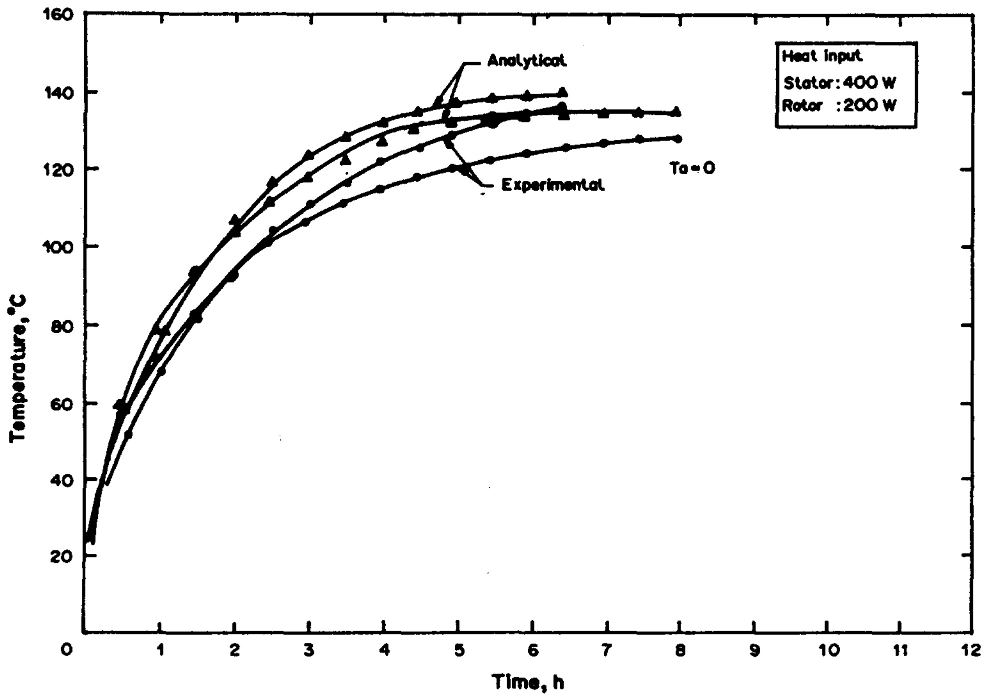

FIG. 6. Variation of temperature of a typical stator and rotor node with time.

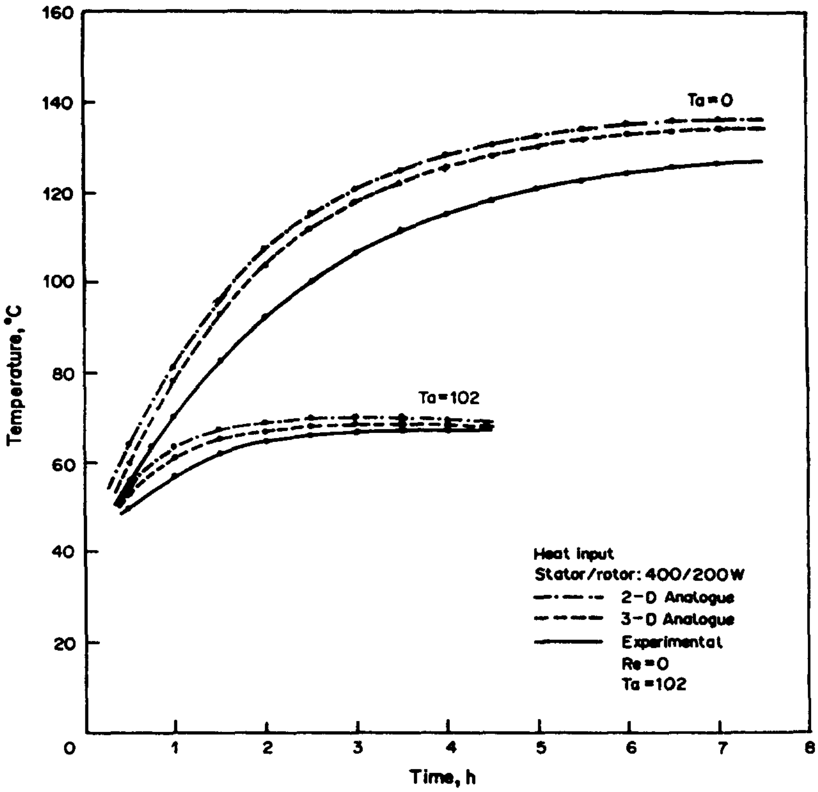

FIG. 7. Comparison of temperature variation of a typical stator node for different *Ta*.

CONCLUSIONS

(1) The unsteady state heat transfer coefficients are significantly different from the steady state values. This fact can be used for better thermal design of the rotating electrical machines.

(2) The simple network analogue method can be effectively used to estimate the transient temperature distribution in rotating systems.

(3) Neither Taylor number nor heat flux appears to have any significant effect on the axial temperature distribution of the disks.

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TRANSFERT THERMIQUE VARIABLE PAR CONVECTION NATURELLE POUR DES DISQUES CONCENTRIQUES CO-ROTATIFS

Résumé—On conduit des études expérimentales pour la détermination des coefficients variables de transfert thermique entre des disques parallèles co-rotatifs avec génération thermique interne. Le modèle expérimental simule un moteur à induction typique avec des pertes différentes dans le stator et le rotor au départ. Les résultats collectés couvrent un domaine de nombres de Taylor pour différentes conditions thermiques. On mesure les températures dans les directions axiale, radiale et tangentielle. Des coefficients variables de transfert thermique vers l'air ambiant on été évalués dans la section radiale. Les résultats du réseau R-C correspondant sont obtenus sur un ordinateur. Les valeurs prédites de température aux points nodaux correspondants sont comparées aux valeurs mesurées et on trouve un bon accord. Les résultats sont utilisables dans la conception des machines électriques, plus spécifiquement dans les moteurs à induction radialement ventilés.

INSTATIONÄRE FREIE KONVEKTION AN GLEICHSINNIG ROTIERENDEN KONZENTRISCHEN SCHEIBEN

Zusammenfassung—Die instationären Wärmeübergangskoeffizienten zwischen zwei parallelen, gleichsinnig rotierenden konzentrischen Scheiben mit innerer Wärmefreisetzung werden experimentell bestimmt. In dem Versuchsmodell wird ein typischer Induktionsmotor nachgebildet mit unterschiedlichen Verlusten im Stator und Rotor beim Anlaufen. Die Versuchsdaten decken bei unterschiedlicher Wärmezufuhr einen Bereich von Taylor-Zahlen ab. Das Anwachsen des Wärmeübergangs mit der Drehzahl unter den Bedingungen der Freien Konvektion wird quantitativ berücksichtigt. Die Temperaturverteilung wird in axialer, radialer und tangentialer Richtung gemessen. In dem sich in radialer Richtung erweiternden Abschnitt werden instationäre Wärmeübergangskoeffizienten zur umgebenden Luft hin berechnet. Das gesamte Problem wird mit Hilfe eines Widerstandskapazitätennetzwerks auf einem digitalen Rechner nachgebildet. Ein Vergleich von Messung und Berechnung zeigt gute Übereinstimmung. Die Ergebnisse sind möglicherweise bei der thermischen Auslegung elektrischer Maschinen sehr nützlich, insbesondere bei radial belüfteten Induktionsmotoren.

НЕСТАЦИОНАРНЫЙ СВОБОДНОКОНВЕКТИВНЫЙ ТЕПЛОПЕРЕНОС В СИСТЕМЕ ИЗ ВРАЩАЮЩИХСЯ В ОДНОМ НАПРАВЛЕНИИ КОНЦЕНТРИЧЕСКИХ ДИСКОВ

Аннотация—Проведены экспериментальные исследования по определению коэффициентов нестационарного теплопереноса в системе параллельных вращающихся в одном направлении и концентрически неподвижных дисков с внутренним тепловыделением. Такая экспериментальная ситуация моделирует типичный асинхронный двигатель с неравными потерями в статоре и роторе при запуске. Получены данные в диапазоне чисел Тэйлора, соответствующем различным тепловым нагрузкам. Определена качественная зависимость интенсивности теплопереноса от скорости вращения дисков при наличии свободной конвекции в окружающей среде. Получены температурные распределения в аксиальном, радиальном и тангенциальном направлениях. Рассчитаны коэффициенты нестационарного теплопереноса в окружающий воздух в радиально расходящемся сечении. С помощью цифровой вычислительной машины получены результаты для соответствующей РС-цепочки. Найдено, что расчетные значения температуры в узловых точках хорошо согласуются с экспериментальными данными. Полученные результаты могут быть использованы при тепловом расчете электрических машин, точнее, радиально вентилируемых асинхронных двигателей.