LIMITING EFFECT OF THERMAL CONDITIONS ON THE CHARACTERISTICS OF FUEL CELLS

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Methods of calculating and measuring the temperature fields of fuel cells are analyzed, in order to determine the maximum allowable temperature-limited electric loading.

During the evolution from electrodes to fuel cells and, especially, from cells to electrochemical generators, there arose problems in distributing the gas flow, in dissipating the excess heat, in disposing of the reaction products, as well as of the accumulated inert gases, etc. Here the authors consider only the effect of thermal conditions on the characteristics of fuel cells. A drop in the operating temperature of hydrogen–oxygen fuel cells results in a lower delivered power, while a rise in the operating temperature results in the impairment of such a cell. Thus, an efficient and trouble-free operation of an electrochemical generator requires a solution to the problem of thermostatizing the device within narrow limits.

In this study we consider fuel cells from which the excess heat is removed by a coolant, namely by a heat carrier which feeds into special heat exchangers built into the fuel cells, also by evaporation of water from the surface of the electrodes, and by cooling of the passages for the vapor–hydrogen mixture to a lower temperature.

We will consider an approximate method of calculating the temperature field, which is based on a substantial simplification of the processes occurring in fuel cells. We assume that the heat sources generated by the electrochemical reaction and the heat sinks generated by evaporation and by cooling with the vapor–hydrogen mixture are uniformly distributed over the surface of the electrodes, while the coolant temperature remains the same between entrance to and exit from the fuel cell. Under the said assumptions, with negligible heat leakage from the end surfaces, the thermal conditions in a fuel cell can be treated as a one-dimensional problem of heat conduction in a multilayer system consisting of infinitely large plates with the heat sources distributed over the interfaces between them and with boundary conditions of the third kind.

Expressing the steady-state temperature profile across the thickness of the i-th layer in terms of the thermal flux passing through that layer, with the thermal fluxes related to the coolant temperature at the boundaries and to the power of the heat sources

$$t_i = t'_{x/a} + q_1R_1 + q_2R_2 + \ldots + q_{i-1} + q_i\,\frac{x-(\delta_1+\ldots+\delta_{n-1})}{\delta_n},$$

$$q_1R_1 + q_2R_2 + \ldots + q_{n-1}R_{n-1} + q_nR_n = t''_{x/a} - t'_{x/a}, \tag{1}$$

$$q_{i+1} = q_i - p_i,$$

we can, regardless of the number of layers, determine the thermal fluxes and thus the temperatures in them:

$$q_1 = \frac{p_1R_2 + (p_1+p_2)R_3 + \sum_{i=1}^{3} p_iR_4 + \ldots + \sum_{i=1}^{n-1} p_iR_n + (t''_{x/a} - t'_{x/a})}{\sum_{i=1}^{n} R_i},$$

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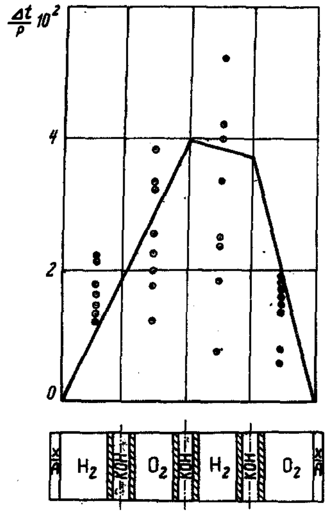

Fig. 1

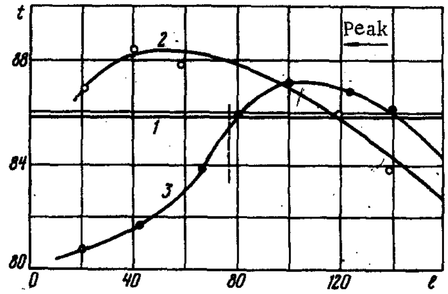

Fig. 2

Fig. 1. Calculated and measured temperature profile across the thickness of a fuel cell.

Fig. 2. Temperature distribution (t, °C) over the electrode surface (l, mm) in the test cell: 1) calculated values; 2) test values; 3) test values with partially drained electrolyte; dashed line indicates the electrolyte level.

$$q_2 = \frac{-p_1R_1 + R_3p_2 + \sum_{i=2}^{3} p_iR_4 + \ldots + \sum_{i=2}^{n-1} p_iR_n + (t''_{x/a} - t'_{x/a})}{\sum_{i=1}^{n} R_i},$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$q_{n-1} = \frac{-[\sum_{i=1}^{1} p_1R_i - \sum_{i=1}^{2} p_2R_i - \ldots - \sum_{i=1}^{n-2} p_{n-2}R_i + \sum_{i=n-1}^{n-1} p_iR_n + (t''_{x/a} - t'_{x/a})}{\sum_{i=1}^{n} R_n}, \tag{2}$$

$$q_n = \frac{-\sum_{i=1}^{n} p_1R_i - \sum_{i=1}^{2} p_2R_i - \ldots - \sum_{i=1}^{n-1} p_{n-1}R_i + (t''_{x/a} - t'_{x/a})}{\sum_{i=1}^{n} R_n}.$$

Let us calculate the temperature fields of a fuel cell containing three pairs of electrodes with interlayers of electrolyte and of gas and with one heat exchanger at each edge (Fig. 1). The thermal resistances of the gas interlayers are at least by one order of magnitude higher than the thermal resistances of the electrodes and of the electrolyte interlayers, which allows us to disregard the latter and thus to greatly simplify the system of equations (2). The superheat in the layers is conveniently represented by the ratio $\Delta t/p$, i.e., in a form independent of the operating mode of the cell. The results of our calculations are shown in Fig. 1 (solid lines).

The heat sources in a real fuel cell are distributed nonuniformly over the surface of the electrodes, because inert impurities in the reagents and gas bubbles in the electrolyte accumulate on part of that surface, because the evaporation and the removal of heat by the vapor–gas mixture are also nonuniform, etc. The actual temperatures will, therefore, differ appreciably from those calculated by the given method, and an experimental study of fuel cell operation becomes especially important.

In a specially built fuel cell consisting of one electrode pair with lateral heat exchangers, the temperature field was measured on the surface of the electrodes under conditions of electric loading and coolant flow, with thermocouples welded to the electrodes by a special technique. The temperature readings

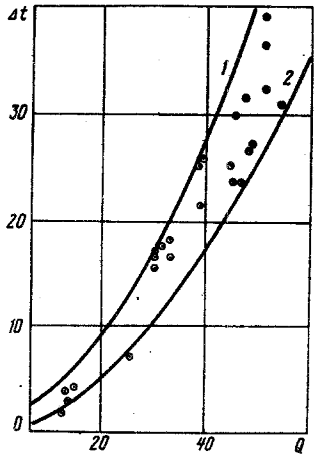

Fig. 3

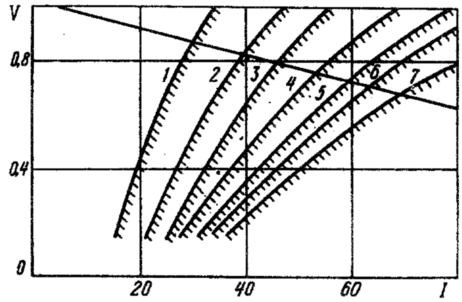

Fig. 4

Fig. 3. Maximum superheat (Δt, °C) as a function of the thermal power (Q, W) in the fuel cell: 1) unfavorable conditions; 2) favorable conditions.

Fig. 4. Nomogram for establishing limits for thermal conditions under electrical loading of fuel cells: 1) Δt = 10°C; 2) 15; 3) 20; 4) 25; 5) 30; 6) 35; 7) 40.

are compared in Fig. 2 with calculations made according to formulas (2) for several operating modes. It is to be noted that the average test values of Δt agree with the calculations. The spread of the test values is quite wide, however, and some regularity (a temperature decrease toward the periphery, because of lateral heat leakage) is accompanied by temperature fluctuations due to the said random effects such as, for example, the presence of large gas bubbles in the electrolyte. It may be expected that the current generating reaction terminates in the bubble region, while the remaining surface becomes heavier loaded. This effect can be modulated by lowering the level of electrolyte in the cell. The temperature field shown in Fig. 2 confirms this hypothesis.

The problem of determining the maximum temperature deviation from the design level in fuel cells was solved on a special apparatus where the operating conditions of a single fuel cell were duplicated in a generator setup with temperature probes in the gas interlayers, with instruments for measuring the flow rates of reagents, coolant, drain water, and instruments for measuring the electrical parameters, etc. The heat balance and the value of p were determined on the basis of experiments. The test data pertaining to temperature fields under various operating modes of the fuel cell are given in Fig. 1 in terms of the Δt/p ratio. A comparison between averaged test data and calculated values indicates a general agreement between both, but also a spread comparable to the mean values. For practical purposes, therefore, it is desirable to determine how the temperature field depends on the operating parameters with only the predominant factors taken into account. Accordingly, the authors selected the maximum superheat Δt_m (the difference between coolant exit temperature and maximum temperature inside the fuel cell) as a function of the thermal power of the fuel cell Q, this power being found from the electrical power and the efficiency.

From various tests at the same value of Q and different values of the other parameters one can find the values of Δt_m and plot the relation $\Delta t_m = f(Q)$ in the form of an allowable zone (Fig. 3) whose upper boundary line refers to the concurrence of unfavorable factors affecting the temperature rise. Thus, the upper boundary of this zone can be used for establishing the maximum allowable heat generation in a fuel cell and, therefore, also the troublefree modes of operation, if the maximum allowable temperature of the fuel cell is specified on the basis of any given considerations. This temperature may be stipulated, for example, by the requirement that the structural materials do not break down or that the electrolytes do not come to boiling.

Since the same amount of heat can be generated at various values of current and voltage, hence it is convenient to represent the relation $\Delta t_m = f(Q)$ in the form of a nomogram on which both the superheat values and the volt–ampere characteristic of the fuel cell have been plotted (Fig. 4). Knowing the maximum allowable superheat, one can find the point on the volt–ampere curve above which the load must not be increased on account of excessive heat generation.

In the development of new cells, when it is necessary to employ design methods, such a form of the $\Delta t_m = f(Q)$ relation becomes useful, after p has been determined as the difference between Q and the heat dissipated by evaporation and cooling with the vapor–gas mixture, and after Δt_m has been found by solving the system of equations (2).

NOTATION

Δt_i is the temperature difference across the i-th layer;
R_i is the thermal resistance of the i-th layer;
p_i is the thermal power generated at the interface between the i-th and the (i + 1)-th layer;
Q is the thermal power in the fuel cell;
q_i is the thermal flux in the i-th layer.