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Analysis of mass exchangers based on dimensionless numbers

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ABSTRACT

A new model approach for an analytical calculation of a mass exchanger is presented in this work. By using three dimensionless numbers the mass transfer between two fluid flows can be calculated dependent on the flow geometry. A gas humidifier used for fuel cell application, which transfers water between two gas flows, is used as an example to illustrate the development of the operation characteristics for coflow, counterflow and crossflow. In this model approach the whole mass transfer process, governed by humidifier design and separator material properties, is described based on a single characteristic value, the effective mass transfer coefficient. The model provides a deeper understanding and prediction capability of the transfer processes which is helpful for mass exchanger designing and controlling. The coflow and counterflow case is validated by using a water permeable membrane as separator of wet air and dry air. Measurement data of a hollow fibre separator is used to validate the cross flow operated humidifier.

1. Introduction

The laws of mass exchange play an important role in process engineering fields where the state of mixtures is changed. Often mass exchange is directly linked to heat exchange, for example when vaporisation or condensation occurs. In such cases the process of mass transfer is not independent of the character of the simultaneous heat transfer. For practical applications heat transfer occurs somewhere between its theoretical limits of isothermal and adiabatic process conditions. For vaporization or condensation heat transfer even becomes the dominant influence on mass transfer. As a consequence, for practical handling of mass transfer processes heat transfer has to be accounted too. The same holds true for the phase equilibrium law‘s on boundary surfaces, the place where concentration gradients are formed.

Generally speaking, there are three resistances to be taken into account. One convective resistance in each fluid and one diffusive across the separator medium. For practical applications all resistances can be combined in one overall effective resistance. The effective heat transfer coefficient is used for heat transfer applications as is the effective mass transfer coefficient for mass transfer.

Today, the processes of heat exchange is sufficiently known for designing a heat exchanger which transfers heat from a hot fluid to a cold one [1–3]. For simple two-flow heat exchangers the analytical NTU-Method is a proper method for describing the operation characteristics. The NTU-Method is based on the three dimensionless numbers dimensionless temperature, number of transfer units (NTU) and heat capacity flow rate ratio. With approximate linearisation a mass exchanger should be described in a similar way owing to analogy between heat and mass transfer. To the best knowledge of the authors, this has never been published. Developing a similar method to describe a mass exchanger is content of this work. Like the overall heat transfer coefficient for heat exchange, the effective mass transfer coefficient represents all mass transfer resistances of the mass exchange process. With the example of a gas humidifier for fuel cell applications the presented analysis is validated.

Gas humidification plays an important role in fuel cell technology. Modern polymer-electrolyte-membrane (PEM) fuel cells require preconditioned process gases. In particular cases where the fuel cell is to be operated with air instead of pure oxygen, there is a risk of drying out the membrane within the fuel cell due to dry air. Air humidifiers are used to prevent this. During operation PEM fuel cells produce water which is carried out by the exhaust air flow. To humidify the fresh air a humidifier can be used. The air humidifier is a typical mass exchanger. It exchanges water from the fuel cell air exhaust to the fuel cell air inlet, as shown in Fig. 1. Usually the air humidity at the fuel cell inlet is controlled by opening and closing of a bypass flow path to the humidifier. This form of humidity control includes the actual state signal from a humidity sensor and a temperature sensor which are both

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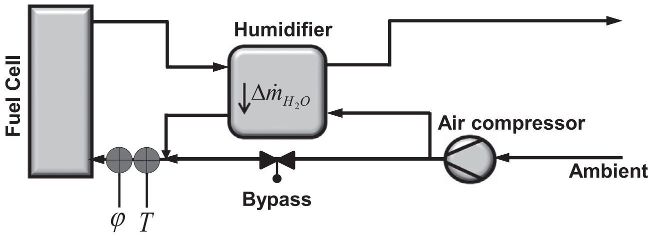

Fig. 1. Air humidity control principle of a PEM fuel cell stack.

integrated into the path downstream of the humidifier and upstream of the fuel cell. The operating characteristics of the humidifier change with

- fuel cell load and therefore product water formation,
- relative air humidity of the ambient,
- dry air mass flow rate provided by the air compressor,
- dry air mass flow rate exhausting the fuel cell,
- air temperatures,
- temperature of the humidifier,
- effective transfer area of the humidifier,
- thickness and properties of the separator,
- operation pressures and
- pressure drop across the humidifier.

A dry air mass flow rate is defined as the rate of flow not including the water. The listed parameters may mutually influence each other, making a dynamic and precise control of the air humidity a challenging task. The following section presents an analytical model to describe the mass transfer within such a humidifier which permits an analytical calculation of the relative humidity at the air-side inlet of the fuel cell. This analytical model of the humidifier might provide options to replace some or even all of the gas humidification sensors. The use of a predictive, model-based pre-control system for gas humidification promises improved dynamic behaviour of the humidification control of PEM fuel cell systems.

2. Model of mass exchanger

Mass transfer processes are ubiquitous in nature and play an important role in various engineering processes in which the state of a mixture of constituents is changed. In particular, these are physical separation processes and numerous chemical reactions. A general challenge of mass transport is that the substance of interest can be unevenly distributed in the carrier medium. This uneven distribution is described by concentration gradients, whereby the gradients themselves are the driving forces for the mass transport.

2.1. General equations

According to Fick‘s Law [4], the diffusive molar flux can be written as

$$j_i = -D \cdot \frac{dc_i}{dy}. \tag{1}$$

In this equation D is the diffusion coefficient and $\frac{dc_i}{dy}$ the molar concentration gradient of component i. The molar concentration of the component c_i is defined as

$$c_i = \frac{\dot{n}_i}{\dot{V}}, \tag{2}$$

where $\dot{V}$ denotes the total volume flow rate.

A separator separates two molar flow rates $\dot{n}_1$ and $\dot{n}_2$ from each other. These flow rates consist of binary mixtures with the two components a and b. The two molar flow rates can be written as

$$\dot{n}_1 = \dot{n}_{1a} + \dot{n}_{1b} = \dot{V}_1 \cdot (c_{1a} + c_{1b}) \quad \text{and} \tag{3}$$

$$\dot{n}_2 = \dot{n}_{2a} + \dot{n}_{2b} = \dot{V}_2 \cdot (c_{2a} + c_{2b}). \tag{4}$$

The separator is permeable for the component b and impermeable for the component a, as seen in Fig. 2. Only $\dot{n}_b$ varies along the transfer area within a mass exchanger. Fig. 3 shows a general sketch of a mass exchanger. Variables with one prime denote the inlet and those with a double prime denote the outlet of the mass exchanger. The requirement that the component $\dot{n}_a$ remains constant yields

$$\dot{n}''_{1a} = \dot{n}'_{1a} \quad \text{and} \tag{5}$$

$$\dot{n}''_{2a} = \dot{n}'_{2a}. \tag{6}$$

The molar flow rate $\Delta\dot{n}_b$ of the component b transferred by the mass exchanger can be calculated by forming balances for the two molar flow rates $\dot{n}_1$ and $\dot{n}_2$.

$$\Delta\dot{n}_{1b} = \dot{n}'_1 - \dot{n}''_1 = (\dot{n}'_{1a} + \dot{n}'_{1b}) - (\dot{n}''_{1a} + \dot{n}''_{1b}) = \dot{n}'_{1b} - \dot{n}''_{1b} \tag{7}$$

$$\Delta\dot{n}_{2b} = \dot{n}'_2 - \dot{n}''_2 = (\dot{n}'_{2a} + \dot{n}'_{2b}) - (\dot{n}''_{2a} + \dot{n}''_{2b}) = \dot{n}'_{2b} - \dot{n}''_{2b} \tag{8}$$

The transfer of mass between $\dot{n}_{1b}$ and $\dot{n}_{2b}$ causes one of the two flows to decrease and the other consequently to increase. Thus, the relationship between the change in both flows is given by

$$\Delta\dot{n}_{1b} = -\Delta\dot{n}_{2b} = \Delta\dot{n}_b. \tag{9}$$

Based on the assumption that the molar flow rates $\dot{n}_1$ and $\dot{n}_2$ as well as the volume flow rates $\dot{V}_1$ and $\dot{V}_2$ remain almost constant, i.e. $\dot{n}'_1 \approx \dot{n}''_1 = \dot{n}_{1a} + \dot{n}_{1b} \gg \Delta\dot{n}_b$, the transferred molar flow rate can be calculated for (nearly) isothermal and isobaric conditions using Eqs. (2)–(4), (7) and (8).

$$\begin{aligned} \Delta\dot{n}_b &= \dot{n}'_{1b} - \dot{n}''_{1b} = \frac{c'_{1b}}{c'_{1a}} \cdot \dot{n}'_{1a} - \frac{c''_{1b}}{c''_{1a}} \cdot \dot{n}''_{1a} \\ &\approx \frac{c'_{1b}}{c'_{1a}} \cdot \dot{n}'_{1a} - \frac{c''_{1b}}{c'_{1a}} \cdot \dot{n}'_{1a} = (c'_{1b} - c''_{1b}) \frac{\dot{n}'_{1a}}{c'_{1a}} \end{aligned} \tag{10}$$

$$\begin{aligned} -\Delta\dot{n}_b &= \dot{n}'_{2b} - \dot{n}''_{2b} = \frac{c'_{2b}}{c'_{2a}} \cdot \dot{n}'_{2a} - \frac{c''_{2b}}{c''_{2a}} \cdot \dot{n}''_{2a} \\ &\approx \frac{c'_{2b}}{c'_{2a}} \cdot \dot{n}'_{2a} - \frac{c''_{2b}}{c'_{2a}} \cdot \dot{n}'_{2a} = (c'_{2b} - c''_{2b}) \frac{\dot{n}'_{2a}}{c'_{2a}} \end{aligned} \tag{11}$$

To calculate the infinitesimal mass transfer $d\dot{n}_b$, an infinitesimal area element dA of the separator is considered, as can be seen in Fig. 4. The transport of mass $d\dot{n}_b$ through the area element dA can be described by

$$d\dot{n}_b = dc_{1b} \cdot \frac{\dot{n}'_{1a}}{c'_{1a}} \tag{12}$$

for the infinitesimal concentration change of $\dot{n}_1$,

$$d\dot{n}_b = -dc_{2b} \cdot \frac{\dot{n}'_{2a}}{c'_{2a}} \tag{13}$$

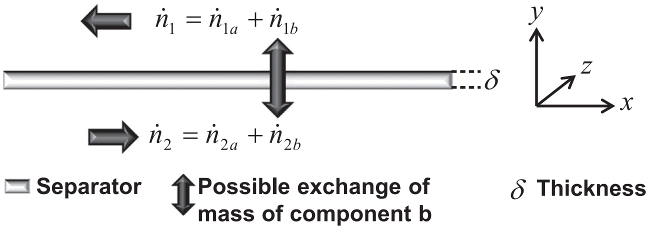

Fig. 2. Two molar flows separated by a separator.