EXPERIMENTAL STUDY CONCERNING THE INVERSION OF CONVECTIVE FLOW IN THE LAMINAR SUBLAYER OF A TURBULENT BOUNDARY LAYER WITH CARBON DIOXIDE INJECTED THROUGH A HEATED VERTICAL POROUS SURFACE IN THE NATURAL CONVECTION MODE

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Results are shown of an experimental study concerning the inversion process in the laminar sublayer of a turbulent boundary layer. Formulas are derived for determining the dimensionless coefficients of heat and mass transfer within the inversion zone.

At a heated vertical surface there appear lift forces Gr_{Tx} acting upward along that surface. During injection of a gas heavier than carbon dioxide of the mainstream there appear lift forces Gr_{mx} opposing those forces due to heating the vertical surface.

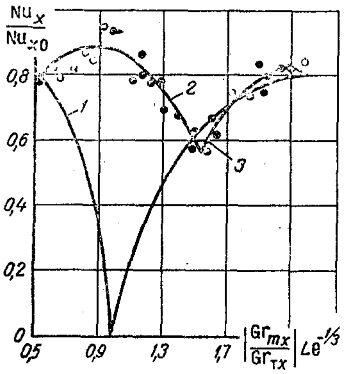

Fig. 1

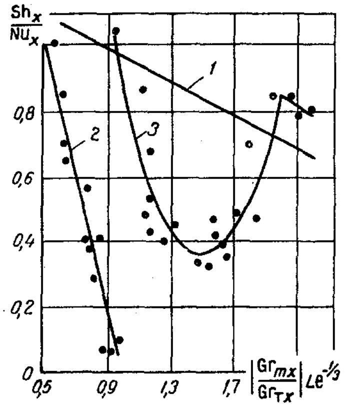

Fig. 2

Fig. 1. Ratio Nu_x/Nu_{x0} for the inversion zone of convection in the laminar sublayer during injection of CO_2 into a turbulent boundary layer: analytical solution according to [3] (1), equation $Nu_x/Nu_{x0} = 0.0408\,\gamma^3 - 0.8928\,\gamma^2 + 1.4421\,\gamma + 0.2822$ (2), equation $Nu_x/Nu_{x0} = -3.565 + 4.2554\,\gamma - 1.0323\gamma^2$ (3). Dots represent test data.

Fig. 2. Ratio Sh_x/Nu_x for the inversion zone of convection in the laminar sublayer (not accounting for the Stefan current) during injection of CO_2 into a turbulent boundary layer: analytical solution according to [3] (1), equation $Sh_x/Nu_x = 2.1615 - 2.1615\,\gamma$ (2), equation $Sh_x/Nu_x = 2.2404\gamma^2 - 6.7004\gamma + 5.3514$ (3). Dots represent test data.

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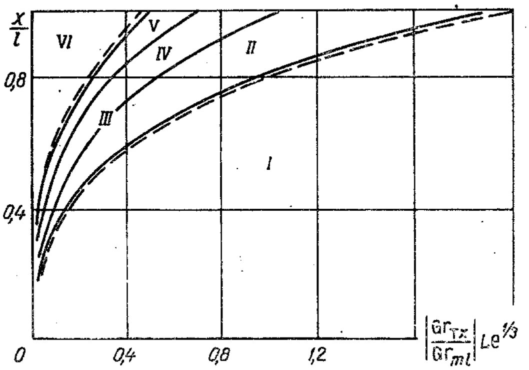

Fig. 3. Determining the locations of zones along the surface, on the basis of the value of parameter $|Gr_{Tx}/Gr_{ml}|Le^{1/3}$ (solid lines represent test data, dashed lines represent the analytical solution according to [3]): zone I before inversion of the laminar sublayer $0 < \gamma < 0.525$, zone II $0.525 < \gamma < 0.965$, zone III $\gamma \approx 0.965$, zone IV $0.965 < \gamma < 1.54$, zone V $1.54 < \gamma < 2.04$, zone VI after inversion of the laminar sublayer.

Depending on the ratio of the two lift forces, the resulting convective velocity in the laminar sublayer may be directed upward ($Gr_{Tx} > Gr_{mx}$) or downward ($Gr_{Tx} < Gr_{max}$).

Inversion of convective flow in the laminar sublayer during injection of a heavy gas into a turbulent boundary layer of air is a phenomenon related to a change in the direction of the convective velocity in the laminar sublayer, to a buildup of the laminar sublayer thickness, and to a reduction in the turbulence with a gradual transformation of the turbulent boundary layer into a laminar one.

A study was made concerning the relation between the dimensionless coefficients of heat and mass transfer and the velocity of CO_2 injection.

The basic parameters were varied over the following ranges:

$$\frac{T_\omega}{T_\infty} = 1.08 - 1.245; \quad Gr_{Tx} = 8.36 \cdot 10^8 - 3.3 \cdot 10^{10};$$

$$|Gr_{mx}| = 1.82 \cdot 10^8 - 4.14 \cdot 10^{10};$$

$$Gr_{hx} = -2.88 \cdot 10^{10} - 3.152 \cdot 10^{10};$$

$$v_\omega = 0.0174 \cdot 10^{-2} - 0.432 \cdot 10^{-2} \text{ m/sec};$$

$$Re_{wx} = 8.9 \div 396; \quad Le_w = 0.81 - 1.2.$$

The physical parameters of the binary mixture were estimated on the basis of the Lennard–Johnson potential [1]. The surface temperature and concentration were regarded as the respective reference quantities.

The experiments were performed with a model IZK-454 interferometer operating in the single-beam mode. The temperature fields were measured with a movable thermocouple [2].

The ratios Nu_x/Nu_{x0} and Sh_x/Nu_x have been plotted respectively in Figs. 1 and 2 as functions of the parameter $|Gr_{mx}/Gr_{Tx}|Le_s^{-1/3} = \gamma$.

The dimensionless coefficient of mass transfer Sh_x does not account for the Stefan current but represents the change in the diffusion current of the active component in the mixture.

During injection of a heavy gas into a turbulent boundary layer of air there emerge six different zones with different heat and mass transfer trends. In zones I and VI (before and after inversion) the dimensionless coefficients of heat and mass transfer can be accurately enough determined from the solution in [3]. An analytical solution for the inversion zone in the laminar sublayer does not reflect the true character of the inversion phenomena. Our experiments have made it possible to describe the processes of heat and mass transfer within the inversion zone and to derive calculation formulas.

Inversion in the laminar sublayer begins when $\gamma = 0.525$. The analytically established inversion threshold corresponds to $\gamma = 0.500$.

As γ increases from 0.525 to 0.965, the laminar sublayer of a turbulent boundary layer breaks down fast and this results in a higher rate of heat transfer but a lower rate of diffusive mass transfer due to a lower concentration gradient.

At $\gamma \approx 0.965$ the laminar sublayer has been completely broken down and the heat transfer rate becomes maximum, but its value here is below Nu_{x0} because of less turbulization of the boundary layer at a higher injection rate of heavy gas.

The change of the Sh_x/Nu_x ratio from its minimum to its maximum value indicates a vortical change in the concentration profile.

TABLE 1

Criterial number	Zone					
	I	II	III	IV	V	VI
	$0<\gamma<0,525$	$0,525<\gamma<0,965$	$\gamma\sim0,965$	$0,965<\gamma<1,54$	$1,54<\gamma<2,04$	$\gamma>2,04$
Nu_x	Analytical solution according to [3]	$\frac{Nu_x}{Nu_{x0}} = 0,0408\gamma^3 - 0,8928\gamma^2 + 1,4421\gamma + 0,2822$			$\frac{Nu_x}{Nu_{x0}} = -0,565 + 4,2554\gamma - 1,0323\gamma^2$	Analytical solution according to [3]
Sh_x	Analytical solution according to [3]	$\frac{Sh_x}{Nu_x} = 2,1615 - 2,1615\gamma$	—	$\frac{Sh_x}{Nu_x} = 2,2404\gamma^2 - 6,7004\gamma + 5,3514$		Analytical solution according to [3]

Note: The analytical solution according to [3] is valid for the following ranges of parameter γ.

$$\text{for determining} \quad \frac{Nu_x}{Nu_{x0}} - 0 < \gamma < 0.525, \quad 1.54 < \gamma < \left| \frac{\beta_m}{\beta_T (T_w - T_\infty)} Le^{-\frac{1}{3}} \right|;$$

$$\text{for determining} \quad \frac{Sh_x}{Nu_x} - 0 < \gamma < 0.525; \quad 2.04 < \gamma < \left| \frac{\beta_m}{\beta_T (T_w - T_\infty)} Le^{-\frac{1}{3}} \right|$$

At $\gamma > 0.965$ a laminar sublayer begins to form and build up with a downward convective velocity along the surface.

The buildup of this laminar sublayer within the range $0.965 < \gamma < 1.540$ has an increasing effect on the mass transfer, as it results in a greater increase in the resistance to heat and mass transfer than in the convective velocity within this sublayer. Accordingly, the dimensionless coefficients of heat and mass transfer decrease as the parameter γ increases over that interval.

As γ increases further from 1.54 to 2.04, the processes of heat and mass transfer become more strongly affected by the increase in the convective velocity than by the buildup of this laminar sublayer.

The inversion of convective flow within the laminar sublayer is complete when $\gamma = 2.04$. The analytically established end of the inversion process corresponds to $\gamma = 2.2$.

As γ increases still further, the flow in the boundary layer at a porous surface becomes laminar. At the outer edge of the now laminar boundary layer there periodically appear undular perturbations propagating upward and in opposition to the convective velocity in this layer. These perturbations weaken as γ increases.

The zone containing the sought surface coordinate and, therefore, the formulas for calculating the local dimensionless coefficients of heat and mass transfer are all found from the graphs in Fig. 3.

The formulas for calculating the local dimensionless coefficients of heat and mass transfer, depending on the zone where the surface coordinate is located, are given in Table 1.

NOTATION

T	is the temperature;
v	is the injection velocity;
β_T	is the thermal volume expansivity;
x	is the local space coordinate;
$\beta_m = [(M_2/M_1)-1]/[1 + ((M_2/M_1)-1)m_1$	is the concentrational volume expansivity;
$Nu_x = \alpha x/\lambda$	is the local Nusselt number (convection);
$Sh_x = \alpha_m x/D$	is the local Sherwood number;
$Le = Pr/Sc$	is the Lewis number;
$Gr_{Tx} = g\beta_T(T_s - T_\infty)x^3/\nu^2$	is the Grashof number referred to temperature;
$Gr_{mx} = g\beta_m(m_{1s} - m_{1\infty})x^3/\nu^2$	is the Grashof number referred to concentration.

Subscripts

x	refers to local value;
s	refers to value at the surface;

∞ refers to value beyond the boundary layer;
0 refers to value at an impermeable surface.

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