$$\varepsilon_{TE} = \frac{t_{25} - t_{21}}{t_{11} - t_{21}} \tag{11}$$

It is in good agreement with WPHE effectiveness ε_T calculated by Eqs. presented in Section 2 of this paper. It confirms the accuracy of proposed mathematical model and validity of it for design of WPHEs of the type considered here.

Table 1: Parameters of tested WPHE

Total heat transfer surface area, F_a, m^2	114.2	Heat conductivity of the wall, λ_w, W/(m K)	16
Number of plates, N_p	359	Corrugations height, *b*, m	0.004
Heat transfer surface area of one plate, F_p, m^2	0.32	Corrugations pitch, S, m	0.018
Height of WPHE, m	1.82	Average channel width, W_{ch}, m	0.55
Cross section area of one channel, f_{ch}, m^2	0.0022	Equivalent diameter of channel, d_e, m	0.008
Plate outside diameter, D_o, m	0.626	For hot stream, β_1, degrees	40
Plate thickness, δ_w, m	0.001	For cold stream, β_2, degrees	50
Plate metal	AISI 304	The width of channel entrance (exit), W_{enx}, m	0.4

Table 2: The results of WPHE tests in industry

	Test #1	Test #2	Test #3
Gas flow rate, kg/s	5.55	5.54	4.39
Temperature of hot gas inlet t_{11}, °C	496	495	487
Temperature of hot gas outlet t_{19}, °C	190	198	195
Temperature of cold gas inlet t_{21}, °C	78	75	82
Temperature of cold gas outlet t_{25}, °C	373	380	389
Pressure at column entrance P_{in}, MPa	30	29	30
Pressure at column exit P_{out}, MPa	28.5	27.5	28.5
Ammonia concentration in cold feed gas, %mol	3.3	3.3	3.3
Ammonia concentration in hot gas, %mol	17.2	17.2	17.2
Calculated temperature of cold gas outlet t_{25calc}, °C	382.5	380.9	381.2
Calculated overall heat transfer coefficient U, W/(m^2K)	1,146	1,145	970
Number of heat transfer units NTU (calculated)	6.46	6.45	6.91
Heat transfer effectiveness ε_T (calculated)	0.729	0.728	0.739
Heat transfer effectiveness ε_{TE} (experiment)	0.706	0.726	0.758
Discrepancy, %	-3.2	0.32	2.5
Counter current flow heat transfer effectiveness ε_{Tcc}	0.841	0.840	0.847
The loss of effectiveness due to cross flow, %	13.2	13.2	12.8

The WPHE is installed instead of tubular heat exchanger of heat transfer area 148 m^2 with the length 3,000 mm. WPHE has the weight 1,694 kg instead of 2,992 kg of tubular heat exchanger and occupying volume 0.96 m^3 that is less on 0.48 m^3. This spare volume is used to increase the amount of catalyser in the column. It leads to 15 % rise of ammonia output.

At the same time the cross flow in one pass of WPHE still remains an important factor geopadizing its overall heat transfer performance. To estimate this effect the heat transfer effectiveness for pure counter current flow is calculated according to Shah and Sekulić (2003) by Eq(12)

$$\varepsilon_{Tcc} = \frac{1 - \exp\left[-NTU \cdot (1 - R)\right]}{1 - R \cdot \exp\left[-NTU \cdot (1 - R)\right]} \tag{12}$$

The comparison of total heat transfer effectiveness ε_T with its value for pure counter current flow shows the reduction about 13 %. The analysis of Eq(4) indicates that some reduction of heat transfer effectiveness in one pass is caused by existence of two sub-passes with not symmetrical flow arrangement (2 sub-passes for hot stream – 1 pass for cold stream). It leads to conclusion of advantage of symmetric flow arrangement with equal passes numbers for both streams even with cross flow in separate channels. However due to technological or other reasons, like in our case requirement to remove catalyser dust coming with hot gas, it is important to have not equal passes numbers. In that case, the optimisation of passes arrangement is required