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Estimation of pressure drop in gasket plate heat exchangers

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Abstract. In this paper, we present comparatively different methods of pressure drop calculation in the gasket plate heat exchangers (PHEs), using correlations recommended in literature on industrial data collected from a vegetable oil refinery. The goal of this study was to compare the results obtained with these correlations, in order to choose one or two for practical purpose of pumping power calculations. We concluded that pressure drop values calculated with Mulley relationship and Buonopane & Troupe correlation were close and also Bond's equation gave results pretty close to these but the pressure drop is slightly underestimated. Kumar correlation gave results far from all the others and its application will lead to oversize. In conclusion, for further calculations we will chose either the Mulley relationship or the Buonopane & Troupe correlation.

Keywords: pressure drop, edible oils, gasket plate heat exchangers.

1. Introduction

In order to be placed on the market, vegetable oils are subject to a refining process, when the product is improving both in terms of sensorial quality and stability during shelf storage. Gasket plate heat exchangers (PHE) are customary in all modern vegetable oil refineries. The Chevron type gasket plate heat exchangers were introduced in 1930 with dedication to the food industry because they have very good transfer coefficients and can be easily cleaned [1-4].

The calculation of pressure drop is an important part of the technological dimensioning of gasket plate heat exchangers since the power consumption for pumping is determined by the pressure loss in the equipment.

The estimation of pressure drop in exchangers is made with different correlations recommended in literature. All these correlations take into account the geometry of the equipment, the hydrodynamic regime and the physical properties of fluids.

Due to the regular shape of cross-corrugated passages in the PHEs, numerical models can reproduce with fidelity the geometry when investigating the buoyancy effects on pressure losses [5].

In recent years, the authors use finite element computational fluid dynamics (CFD) for the analysis of tortuosity, shape factor and friction factor determination [6].

Also, the Re-Normalization Group (RNG) method is used for the re-normalization of Navier-Stokes equations in prediction of vortex evolution and the calculation of friction factors and pressure losses [7].

However, different simple correlations developed empirically in laboratory by Kumar, Mulley, Bond, Buonopane, Gulenoglu and other scientists [8-13] can be applied in industrial conditions. The aim of this work was to select a reliable mathematical model from these simple correlations, for the estimation of pressure drop in gasket plate heat exchangers used in the vegetable oil refining industry.

2. Theoretical approach

The chevron-type plate is the most used element for PHEs. The plate corrugations are in form of chevron because this pattern is easy to manufacture. Longitudinal and transversal corrugations are plotted in two separated plans [7] and the corrugation angle can be 30°, 45° or 60°, but most frequently 60°.

In Fig. 1, the chevron- type plate is presented with the principal dimensions, some of them being used in hydrodynamic calculations: L_p- vertical port-to-port channel length, m; L_{eff}- effective length, m; L_h- horizontal port-to-port channel length, m; L_w- width of flow channel, m; D_p- port diameter, m; β- chevron angle, deg.

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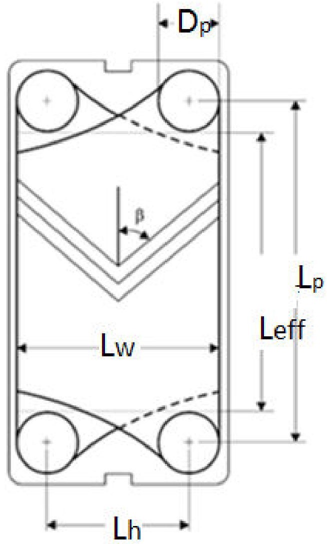

Fig.1.Chevron-type plate

The total pressure drop is the sum of pressure drop in channels and in the ports. It can be estimated with the Eq. (1):

$$\Delta p_t = \Delta p_c + \Delta p_p \quad (1)$$

where Δp_t represents the total pressure drop (Pa), Δp_c– channel pressure drop (Pa), Δp_p– port pressure drop (Pa).

The channel pressure drop is defined by the Eq. (2):

$$\Delta_{p_c} = 4 \cdot f \cdot \left(\frac{L_p \cdot N_p}{d_h}\right) \cdot \left(\frac{G_{ch}^2}{2 \cdot \rho_{c,h}}\right) \cdot \left(\frac{\mu}{\mu_w}\right)^{-0.17} \quad (2)$$

where f represents the friction factor, non-dimensional; L_p –vertical port-to-port channel length, m; N_p – number of passes; d_h –hydraulic diameter, m; G_{ch} – the fluid mass velocity in the channel, kg·m^{-2}·s; $\rho_{c,h}$ – density for the cold respectively for the hot fluid, kg/m^3; μ – dynamic viscosity of fluid at the mean temperature in the apparatus, Pa·s; μ_w – dynamic viscosity of fluids at the wall temperature, Pa·s.

The friction factor f is calculated with different equations from literature as function of Reynolds number and chevron angle.

The pressure drop in the port ducts can be estimated with Eq. (3) [13]:

$$\Delta p_p = 1.4 \cdot N_p \cdot \left(\frac{G_p^2}{2 \cdot \rho_{c,h}}\right) \quad (3)$$

where N_p represents the number of passes, G_p –mass velocity of fluid in the port, kg·m^{-2}·s; $\rho_{c,h}$ – density for cold / hot fluids, kg/m^3.

The mass velocity for the cold and hot fluids in the port is calculated by Eq. (4):

$$G_p = \frac{\dot{m}}{\pi\left(\frac{D_p^2}{4}\right)} \quad (4)$$

where $\dot{m}$ represents the total flow rate in the port opening (kg/s), D_p – the port diameter, m [6, 8, 9].

As one can see in Eq.1-4, the pressure drop in heat exchangers depends on equipment geometry, physical properties of fluids and flow conditions. The friction factor, f, is of great importance and there are dedicated correlations for its estimation.

For example, Kumar correlations (5) and (6) correlate f with the flow regime expressed as Reynolds numbers [13, 14]:

$$f = \frac{19{,}400}{Re^{0{,}589}}, \text{ for } Re = 10 - 100 \quad (5)$$

$$f = \frac{2{,}990}{Re^{0{,}183}}, \text{ for } Re > 100 \quad (6)$$

It is important to know that, according to Kumar's observations, the critical Reynolds value for the transition from the laminar to the turbulent flow in PHEs, is approximately 100 [6,14] since for other authors [15,16] , the turbulent regime starts at Re≅ 400.

The early buoyancy apparition is linked to the shape of cross-corrugated passages and the abrupt change in density and viscosity of fluids due to strong variation of its temperature in a short distance.

Other researchers developed correlations of f with Re, in their own way, following experimental studies. All these equations (Eq. 5-10) are empirical:

- Bond correlation I [13]:

$$f = 3{,}01 \cdot Re^{-0{,}457} \quad (7)$$

- Buonopane & Troupe correlation [11]:

$$f = \frac{2{,}5}{Re^{0{,}3}} \quad (8)$$

- Bond correlation II [9]:

$$f = 2{,}886 \cdot Re^{-0{,}457} \quad (9)$$

- Gulenoglu correlation [12]:

$$f = 259{,}9 \cdot Re^{-0{,}9227} + 1{,}246 \quad (10)$$

Mulley [12] developed a more complex correlation (Eq. 11) taking into account the most important geometrical dimension, from the viewpoint of friction, the corrugation inclination angle relative to vertical direction, β, so called chevron angle:

$$f = \left(\frac{\beta}{30}\right)^{0{,}83} \cdot \left[\left(\frac{30{,}2}{Re}\right)^5 + \left(\frac{6{,}28}{Re^{0{,}5}}\right)^5\right]^{0{,}2} \quad (11)$$

3. Experimental

There were six gasket plate heat exchangers in the industrial plant of different size and with different working fluids (oils with changing properties, cooling water and condensing steam).

In the degumming and neutralization stage, the working fluids are crude oil - bleached oil in PHE #1, crude oil – steam in PHE #2, crude oil – water in PHE #3 and crude oil – steam in PHE #4. In the winterizing stage, the working fluids are bleached oil – water in PHE #5 and in the deodorization stage the working fluids are deodorization oil – water in PHE #6.

The experiment was performed in three campaigns, as follows:

- Campaign 1: processing sunflower oil
- Campaign 2: processing rapeseed oil
- Campaign 3: processing sunflower oil

Every campaign was a few days long, the stock of raw had constant quality during one campaign and the flow rates and temperatures in the process were constant for days. However, inside of each campaign, there were found little changes in flow rates and temperatures, allowing us to have in the end 9 different sets of data for the purposes of this study.

The physical properties of oils (density, viscosity), in all stages of the process, were measured at atmospheric pressure with Anton Parr SVM 3000 apparatus, following the ASTM D445/ISO 121852 method, in the range of 20 ºC-110 ºC, with a precision of ±0,005 ºC for temperature, ±0,0002 g/cm^3 for density and ±0,1% for the viscosity. The variation curves of density and viscosity with temperature were draw and discussed in previous works [17, 18]. Properties for cooling water and steam were found in [19].

With the geometrical characteristics of each heat exchanger and the physical properties of fluid calculated in the working conditions, the pressure drop was calculated for each circuit with the following correlations: Kumar (Eq. 5 or 6 depending on flow regime), Bond I (Eq. 7), Buonopane & Troupe (Eq. 8), Bond II (Eq. 9), Gulenoglu (Eq. 10) and Mulley (Eq. 11).

Results are presented in Tables 1-6, each table corresponding to one of the six PHEs in the industrial plant.

4. Results and Discussions

For gasket plate heat exchanger PHE #1, the working fluids are crude oil - bleached oil. Both fluids are liquid and work in the laminar flow (Re<100). The pressure drop values calculated for this equipment with Eq. 5-11 are presented in Table 1. It can be observed that the highest values of pressure drop are obtained using Kumar relationship Eq. 5, 2-3 times higher than using other methods. Mulley and Buonopane & Troupe correlations give closer results, as also seen in Table 7.

Table 1. Pressure drop in PHE #1 calculated with different correlations

Working fluids	Density, [kg/m^3]	Dinamic viscosity, [Pa·s]	Flow rate, [kg/s]	Reynolds number	Pressure drop, [Pa]	Kumar correlation	Mulley correlation	Bond I correlation	Buonopane & Troupe correlation
First campaing, sunflower oil									
Crude oil	890.0	0.0132	1.736	27	Δp_c	36957	17765	8876	12396
					Δp_p	4	4	4	4
					Δp_t	36961	17769	8880	12400
Bleached oil	877.6	0.0131	2.138	58	Δp_c	40217	19046	1096	16734
					Δp_p	6	6	6	6
					Δp_t	40223	19052	10702	16740
Crude oil	890.0	0.0132	2.049	32	Δp_c	46732	15884	8227	16440
					Δp_p	5	5	5	5
					Δp_t	46,737	15,889	8,232	16,445
Bleached oil	877.6	0.0131	2.524	68	Δp_c	50819	24255	13698	22149
					Δp_p	8	8	8	8
					Δp_t	50827	24263	13706	22157
Crude oil	890.0	0.0132	2.457	39	Δp_c	60339	14173	7571	22376
					Δp_p	8	8	8	8
					Δp_t	60347	14181	7579	22384
Bleached oil	877.6	0.0131	3.026	81	Δp_c	65548	31655	19660	30122
					Δp_p	12	12	12	12
					Δp_t	65560	31667	19672	30134
Crude oil	890.0	0.0132	2.713	43	Δp_c	69399	13358	7236	26485
					Δp_r	9	9	9	9
					Δp_t	69409	13367	7245	26494
Bleached oil	877.6	0.0131	3.342	90	Δp_c	75508	36763	21252	35770
					Δp_p	14	14	14	14
					Δp_t	75522	36778	21266	35784

Second campaign, rapeseed oil									
Crude oil	876.0	0.0162	2.72	45	Δp_c	68356	32150	17558	26562
					Δp_p	9	9	9	9
					Δp_t	68365	32159	17567	26571
Bleached oil	888.80	0.0126	3.35	72	Δp_c	83279	39870	22691	36823
					Δp_p	14	14	14	14
					Δp_t	83293	39884	22705	36837
Third campaign, sunflower oil									
Crude oil	889.9	0.0142	1.736	33	Δp_c	33464	15837	8243	11864
					Δp_p	4	4	4	4
					Δp_t	33468	15841	8247	11868
Bleached oil	877.1	0.011	2.138	53	Δp_c	41509	19587	10870	16827
					Δp_p	6	6	6	6
					Δp_t	41515	19593	10876	16833
Crude oil	889.9	0.0142	2.049	39	Δp_c	42283	19893	10646	15726
					Δp_r	5	5	5	5
					Δp_t	42288	19898	10651	15731
Bleached oil	877.1	0.011	2.524	62	Δp_c	5244	24921	14038	22304
					Δp_p	8	8	8	8
					Δp_t	52455	24929	14046	22312
Crude oil	889.9	0.0142	2.457	47	Δp_c	54631	25706	14088	21414
					Δp_p	8	8	8	8
					Δp_t	54639	25713	14096	21422
Bleached oil	877.1	0.011	3.026	75	Δp_c	67764	32537	18578	30371
					Δp_r	12	12	12	12
					Δp_t	67776	32549	18590	30383
Crude oil	889.9	0.0142	2.713	52	Δp_c	62832	29633	16416	25344
					Δp_r	9	9	9	9
					Δp_t	62841	29642	16426	25353
Bleached oil	877.1	0.011	3.342	82	Δp_c	77935	37668	21648	35945
					Δp_r	14	14	14	14
					Δp_t	77494	37682	21662	35959

The working fluids for gasket plate heat exchanger PHE #2 are crude oil and steam. The results of pressure drop for crude oil – steam are presented in Table 2. Reynolds numbers indicate a turbulent flow either we accept the critical Re>100 [6, 14], or Re>400 [15, 16] for the transition to the turbulent flow. As a consequences, pressure drop on the oil circuit are higher than those in the PDE #1.

It can be observed from Table 2 that the Kumar relationship give the highest values of pressure drops for both oil and steam circuits. The pressure drop on the condensing steam circuit is higher than on oil because the turbulent flow is well developed. By comparing the values of pressure drop in the steam circuit, there are observed high differences, the Kumar correlation giving results tenfold higher than Bond correlation and even differences between the other correlations' results are important. This is due to the fact that all these correlations were produced for liquids working in PHEs.

Table 2. Pressure drop values in PHE #2 calculated with different correlations

Working fluids	Density, [kg/m^3]	Dinamic viscosity, [Pa·s]	Flow rate, [kg/s]	Pressure drop, [Pa]	Reynolds number	Kumar correlation	Mulley correlation	Buonopane & Troupe correlation	Bond I correlation
First campaign, sunflower oil									
Crude oil	874.3	0.0087	1.736	Δp_c	328	50223	39621	24339	11830
				Δp_p		3	3	3	3
				Δp_t		50227	39624	24342	11833
Steam	1.923	0.000015	0.023	Δp_c	9309	121950	14136	35002	10037
				Δp_p		6	6	6	6
				Δp_t		121956	14142	35008	10042
Crude oil	874.3	0.0087	2.049	Δp_c	387	66606	46261	31488	15999
				Δp_p		5	5	5	5
				Δp_t		666611	46266	31493	16004
Steam	1.923	0.000015	0.028	Δp_c	10987	164814	18135	46396	12962
				Δp_p		8	8	8	8

				Δp_t		164822	18143	46396	12970
Crude oil	874.3	0.0087	2.475	Δp_c	467	91885	50814	42167	22536
				Δp_p		7	7	7	7
				Δp_t		91892	50821	42174	22542
Steam	1.923	0.000015	0.033	Δp_c	13175	229239	23802	63175	17155
				Δp_p		11	11	11	11
				Δp_t		229250	23813	63186	17156
Crude oil	874.3	0.0087	2.713	Δp_c	513	107664	77655	48709	26734
				Δp_p		8	8	8	8
				Δp_t		107671	77663	48717	26743
Steam	1.923	0.000015	0.037	Δp_c	14548	274474	27618	74769	19989
				Δp_p		14	14	14	14
				Δp_t		274488	27632	74783	20003
Second campaign, rapeseed oil									
Crude oil	873.0	0.011	2.72	Δp_c	425	18583	93262	57976	18531
				Δp_p		36	36	36	36
				Δp_t		18619	93270	57985	18567
Steam	1.923	0.000015	0.037	Δp_c	14585	274625	27819	74992	20105
				Δp_p		15	15	15	15
				Δp_t		274640	27834	75007	20120
Third campaign, sunflower oil									
Crude oil	873.2	0.0091	1.736	Δp_c	313	58810	43562	26925	22612
				Δp_p		4	4	4	4
				Δp_t		58814	43562	26929	22616
Steam	1.923	0.000015	0.028	Δp_c	9309	121950	14136	35002	10037
				Δp_p		6	6	6	6
				Δp_t		121956	14142	35008	10042
Crude oil	873.2	0.0091	2.049	Δp_c	369	73513	56631	34991	28251
				Δp_p		5	5	5	5
				Δp_t		73518	56636	34996	28256
Steam	1.923	0.000015	0.033	Δp_c	10987	164814	18135	46396	12962
				Δp_p		8	8	8	8
				Δp_t		164822	18143	46396	12970
Crude oil	873.2	0.0091	2.475	Δp_c	443	100100	74357	46307	39294
				Δp_r		7	7	7	7
				Δp_t		100107	74363	46314	39301
Steam	1.923	0.000015	0.033	Δp_c	13175	229239	23802	63175	17155
				Δp_p		11	11	11	11
				Δp_t		229250	23813	63186	17156
Crude oil	873.2	0.0091	2.713	Δp_c	489	118470	86273	53959	47047
				Δp_p		8	8	8	8
				Δp_t		118478	86281	53968	47052
Steam	1.923	0.000015	0.037	Δp_c	14548	274474	27618	74769	19989
				Δp_p		14	14	14	14
				Δp_t		274488	27632	74783	20003

Working fluids for gasket plate heat exchanger PHE#3 are crude oil and water. Table 3 presents the values of pressure drops.

From Table 3, also it can be observed that highest values of pressure drop are obtained with Kumar correlation. Also, there are higher values of pressure drop on water circuit because the mass velocity of water is three times higher than that of oil in similar flow sections; it is to be considered that pressure drop is also dependent on friction factor, *f*, decreasing with Re, and *f* is four times higher in the oil circuit. The combined effect of this two antagonist factors led to pressure drop double in the water circuit.

For gasket plate heat exchanger PHE #4, the working fluids are crude oil and steam. The pressure drop values for this equipment are presented in Table 4.

Table 3. Pressure drop values in PHE #3 calculated with different correlations

Working fluids	**Density, [kg/m^3]**	**Dinamic viscosity, [Pa·s]**	**Flow rate, [kg/s]**	**Pressure drop, [Pa]**	**Reynolds number**	**Kumar correlation**	**Mulley correlation**	**Bond I correlation**	**Buonopane & Troupe correlation**
First campaign, sunflower oil									
Crude oil	888.0	0.0157	1.736	Δp_c	25	13563	11185	3212	4415
				Δp_p		2	2	2	2
				Δp_t		13565	11187	3214	4417
Water	987.9	0.00077	5.251	Δp_c	154	26009	6978	5135	9203
				Δp_p		15	15	15	15
				Δp_t		26024	6993	5150	9218
Crude oil	888.0	0.0157	2.049	Δp_c	29	17136	14570	4149	5852
				Δp_p		3	3	3	3
				Δp_t		17139	14572	4152	5855
Water	987.9	0.00077	6.198	Δp_c	1782	33701	8134	6616	11766
				Δp_p		21	21	21	21
				Δp_t		33723	8156	6637	11788
Crude oil	888.0	0.0157	2.475	Δp_c	35	22142	19634	5491	7969
				Δp_p		4	4	4	4
				Δp_t		22146	19638	5495	7973
Water	987.9	0.00077	7.432	Δp_c	2155	47596	11397	9272	16211
				Δp_p		31	31	31	31
				Δp_t		47627	11428	9303	16242
Crude oil	888.0	0.0157	2.713	Δp_c	39	25476	23182	6402	9437
				Δp_p		5	5	5	5
				Δp_t		25480	23186	6407	9441
Water	987.9	0.00077	8.206	Δp_c	2386	57321	13701	15126	19266
				Δp_p		38	38	38	38
				Δp_t		57359	13740	15164	19304
Second campaign, rapeseed oil									
Crude oil	886.7	0.0152	2.720	Δp_c	40	24608	22824	6211	9201
				Δp_p		5	5	5	5
				Δp_t		24612	22829	6215	9205
Water	987.9	0.00077	8.227	Δp_c	2391	57511	13769	11194	19352
				Δp_p		38	38	38	38
				Δp_t		57549	13807	11232	19390
Third campaign, sunflower oil									
Crude oil	886.9	0.0132	1.736	Δp_c	29	12034	11439	2915	4116
				Δp_p		2	2	2	2
				Δp_t		12036	11441	2917	4118
Water	987.9	0.00077	5.251	Δp_c	1526	25433	6942	5017	9018
				Δp_p		16	16	16	16
				Δp_t		25449	6958	5033	9034
Crude oil	886.9	0.0132	2.049	Δp_c	35	15207	15586	3765	5457
				Δp_p		3	3	3	3
				Δp_t		15210	15589	3788	5460
Water	987.9	0.00077	6.198	Δp_c	1801	34372	7230	6747	11955
				Δp_p		22	22	22	22
				Δp_t		34394	7252	6769	11977
Crude oil	886.9	0.0132	2.475	Δp_c	42	19648	17751	4984	7430
				Δp_p		4	4	4	4
				Δp_t		19651	17755	4988	7434
Water	987.9	0.00077	7.432	Δp_c	2160	47808	11285	9334	16279
				Δp_p		31	31	31	31
				Δp_t		47839	11316	9365	16310
Crude oil	886.9	0.0132	2.713	Δp_c	46	22597	20794	5842	8794
				Δp_p		5	5	5	5
				Δp_t		22602	20799	5847	8799
Water	987.9	0.00077	8.206	Δp_c	2385	5724	13584	1143	19267
				Δp_p		38	38	38	38
				Δp_t		57280	13622	11181	19305

Table 4. Pressure drop values in PHE #4 calculated with different correlations

Working fluids	Density, [kg/m^3]	Dinamic viscosity, [Pa·s]	Flow rate, [kg/s]	Pressure drop, [Pa]	Reynolds number	Kumar correlation	Mulley correlation	Bond I correlation	Buonopane & Troupe correlation
First campaign, sunflower oil									
Crude oil	883.4	0.0128	1.736	Δp_c	102	33443	16312	9495	16278
				Δp_r		14	14	14	14
				Δp_t		33457	16326	9519	16292
Steam	1.923	0.000015	0.050	Δp_c	9104	89006	10390	7370	25613
				Δp_r		73	73	73	73
				Δp_t		89079	10443	7443	25686
Crude oil	883.4	0.0128	2.049	Δp_c	120	45131	20840	12230	21532
				Δp_r		19	19	19	19
				Δp_t		45150	20859	12249	21551
Steam	1.923	0.000015	0.059	Δp_c	10745	120291	13323	9519	33950
				Δp_r		101	101	101	101
				Δp_t		120392	13424	9620	34051
Crude oil	883.4	0.0128	2.475	Δp_c	144	63085	27440	16242	29499
				Δp_r		28	28	28	28
				Δp_t		63113	27468	16270	29527
Steam	1.923	0.000015	0.071	Δp_c	12885	167311	17495	12597	46230
				Δp_r		145	145	145	145
				Δp_t		167456	17640	12742	46375
Crude oil	883.4	0.0128	2.713	Δp_c	159	75320	31778	18912	34792
				Δp_r		35	35	35	35
				Δp_t		75355	31813	18947	34827
Steam	1.923	0.000015	0.078	Δp_c	14228	200326	20299	14678	54714
				Δp_r		177	177	177	177
				Δp_t		200503	20476	14855	54891
Second campaign, rapeseed oil									
Crude oil	882.1	0.0133	2.72	Δp_c	154	83473	35650	21180	38780
				Δp_r		35	35	35	35
				Δp_t		83508	35685	21215	38816
Steam	1.923	0.000015	0.078	Δp_c	14265	209422	20450	14820	55012
				Δp_r		185[1]	185	185	185
				Δp_t		209607	20635	15005	55197
Third campaign, sunflower oil									
Crude oil	882.3	0.0115	1.736	Δp_c	113.4	35936	16906	9894	17273
				Δp_r		14	14	14	14
				Δp_t		35950	16910	9908	17287
Steam	1.923	0.000015	0.050	Δp_c	9104	89006	10390	7370	25613
				Δp_r		73	73	73	73
				Δp_t		89079	10443	7443	25686
Crude oil	882.3	0.0115	2.049	Δp_c	134	48566	21652	12778	22896
				Δp_r		20	20	20	20
				Δp_t		48586	21672	12798	22916
Steam	1.923	0.000015	0.059	Δp_c	10745	120291	13323	9519	33950
				Δp_r		101	101	101	101
				Δp_t		120392	13424	9620	34051
Crude oil	882.3	0.0115	2.457	Δp_c	161	67551	28406	16911	31177
				Δp_r		28	28	28	28
				Δp_t		67579	28434	16939	31205
Steam	1.923	0.000015	0.071	Δp_c	12885	167311	17495	12597	46230
				Δp_r		145	145	145	145
				Δp_t		167456	17640	12742	46375
Crude oil	882.3	0.0115	2.713	Δp_c	177	80881	32948	19705	36899
				Δp_r		35	35	35	35
				Δp_t		80816	32983	19740	36934
Steam	1.923	0.000015	0.078	Δp_c	14228	200326	20299	14678	54714
				Δp_r		177	177	177	177
				Δp_t		200503	20476	14855	54891

The pressure drop in the crude oil circuit in PHE #4 is smaller than in similar PHE #2 because the route length is smaller and the section area is double in PHE #4 comparing with PHE#2. The same can be said about pressure drop on steam circuit. Also, the same considerations made at PHE #2 about the differences between the results calculated with different correlations for the steam circuit are valid for the PHE#4.

Table 5. Pressure drop values in PHE #5 calculated with different correlations

Working fluids	Density, [kg/m^3]	Dinamic viscosity, [Pa·s]	Flow rate, [kg/s]	Pressure drop, [Pa]	Reynolds number	Kumar correlation	Bond I correlation	Buonopane & Troupe correlation	Muley correlation
First campaign, sunflower oil									
Bleached oil	895.2	0.022	1.940	Δp_c	25	26727	6321	8713	13034
				Δp_r		2	2	2	2
				Δp_t		26729	6323	8715	13036
Water	988.4	0.00078	2.546	Δp_c	921	11165	2240	4207	2556
				Δp_r		4	4	4	4
				Δp_t		11169	2244	4211	2560
Bleached oil	895.2	0.022	2.193	Δp_c	28	31757	7653	10718	15268
				Δp_r		3	3	3	3
				Δp_t		31760	7656	10721	15330
Water	988.4	0.00078	2.878	Δp_c	1038	13977	2778	5144	3287
				Δp_r		5	5	5	5
				Δp_t		13982	2783	5149	3292
Bleached oil	895.2	0.022	2.490	Δp_c	32	37996	9314	13315	18071
				Δp_r		4	4	4	4
				Δp_t		38000	9318	13319	18075
Water	988.4	0.00078	3.268	Δp_c	1179	17487	3480	6384	4065
				Δp_r		6	6	6	6
				Δp_t		17493	3486	6390	4158
Bleached oil	895.2	0.022	2.755	Δp_c	35	41614	10838	15808	20734
				Δp_r		5	5	5	5
				Δp_t		41619	10843	15813	20737
Water	988.4	0.00078	3.616	Δp_c	1305	21054	4163	7594	4905
				Δp_r		7	7	7	7
				Δp_t		21061	4170	7601	4912
Second campaign, rapeseed oil									
Bleached oil	893.6	0.018	2.76	Δp_c	38	42012	10525	15455	19781
				Δp_r		5	5	5	5
				Δp_t		42017	10530	15460	19786
Water	988.4	0.00078	3.622	Δp_c	1306	21069	4173	7603	4930
				Δp_r		7	7	7	7
				Δp_t		21076	4180	7610	4937
Third campaign, sunflower oil									
Bleached oil	894.65	0.0206	1.940	Δp_c	30	23577	5739	8141	11227
				Δp_r		2	2	2	2
				Δp_t		23579	5741	8143	11229
Water	988.4	0.00078	2.546	Δp_c	919	11102	2223	4178	2556
				Δp_r		4	4	4	4
				Δp_t		11106	2227	4182	2560
Bleached oil	894.65	0.0206	2.193	Δp_c	34	28029	6935	10027	13243
				Δp_r		3	3	3	3
				Δp_t		28032	6937	10030	13246
Water	988.4	0.00078	2.878	Δp_c	1038	13872	2768	5146	3210
				Δp_r		5	5	5	5
				Δp_t		13877	2773	5151	3215
Bleached oil	894.65	0.0206	2.490	Δp_c	39	33529	8432	12442	15776
				Δp_r		4	4	4	4
				Δp_t		33533	8436	12446	15780
Water	988.4	0.00078	3.268	Δp_c	1179	17473	3474	6386	4065
				Δp_r		6	6	6	6
				Δp_t		17479	3480	6392	4071
Bleached oil	894.65	0.0206	2.755	Δp_c	43	38672	9854	14776	18181
				Δp_r		5	5	5	5
				Δp_t		38677	9859	14781	18186
Water	988.4	0.00078	3.616	Δp_c	1304	21003	4162	7584	4905
				Δp_r		7	7	7	7
				Δp_t		21010	4169	7591	4912

The working fluids for gasket plate heat exchanger #5 are bleached oil and water. The calculated pressure drop values for bleached oil and water are presented in Table 5.

In this case too, the pressure drops calculated by Kumar relationship are higher than with other methods. The methods of Bond, Mulley and Buonopane give closer values.

In the heat exchanger #6 the working fluids are deodorized oil – water. The pressure drop values for this equipment are presented in Table 6.

Table 6. Pressure drop values in PHE #6 calculated with different correlations

Working fluids	Density, [kg/m^3]	Dinamic viscosity, [Pa·s]	Flow rate, [kg/s]	Pressure drop, [Pa]	Reynolds number	Kumar correlation	Bond I correlation	Buonopane & Troupe correlation	Mulley correlation
First campaign, sunflower oil									
Deodorized oil	879.2	0.0109	1.736	Δp_c	19	4904	1123	1484	2500
				Δp_r		2	2	2	2
				Δp_t		4906	1125	1486	2502
Water	986.75	0.00074	6.02	Δp_c	979	10533	2099	3937	2437
				Δp_r		24	24	24	24
				Δp_t		10558	2124	3962	2457
Deodorized oil	879.2	0.0109	2.049	Δp_c	23	6137	1449	1963	3059
				Δp_r		3	3	3	3
				Δp_t		6140	1451	1966	3062
Water	986.75	0.00074	7.100	Δp_c	1154	14186	2827	5205	3316
				Δp_r		28	28	28	28
				Δp_t		14215	2855	5234	3345
Deodorized oil	879.2	0.0109	2.475	Δp_c	27	8003	1920	2678	3854
				Δp_r		4	4	4	4
				Δp_t		8007	1924	2682	3858
Water	986.75	0.00074	8.500	Δp_c	1379	19611	3706	7046	4646
				Δp_r		41	41	41	41
				Δp_t		19652	3747	7087	4688
Deodorized oil	879.2	0.0109	2.713	Δp_c	30	9205	2234	3171	4389
				Δp_r		5	5	5	5
				Δp_t		9210	2239	3176	4394
Water	986.75	0.00074	9.400	Δp_c	1528	23614	4656	8375	5584
				Δp_r		50	50	50	50
				Δp_t		23664	4706	8425	5634
Second campaign, rapeseed oil									
Deodorized oil	878.7	0.012	2.720	Δp_c	27	9449	2268	3167	4543
				Δp_r		5	5	5	5
				Δp_t		9454	2273	3172	4547
Water	986.75	0.00074	9.436	Δp_c	1533	23868	4708	8458	5612
				Δp_r		50	50	50	50
				Δp_t		23919	4758	8509	5663
Third campaign, sunflower oil									
Deodorized oil	879.2	0.0116	1.736	Δp_c	18	4915	1117	1461	2540
				Δp_r		2	2	2	2
				Δp_t		4917	1119	1463	2542
Water	986.75	0.00074	6.022	Δp_c	979	10568	2113	3947	2440
				Δp_r		20	20	20	20
				Δp_t		10589	2133	3968	2460
Deodorized oil	879.2	0.0116	2.049	Δp_c	21	6210	1442	1936	3098
				Δp_r		3	3	3	3
				Δp_t		6213	1445	1939	3101
Water	986.75	0.00074	7.108	Δp_c	1156	14283	2841	5233	3320
				Δp_r		29	29	29	29
				Δp_t		14312	2870	5261	3349
Deodorized oil	879.2	0.0116	2.457	Δp_c	26	8024	1909	2637	3890
				Δp_r		4	4	4	4
				Δp_t		8028	1913	2641	3894
Water	986.75	0.00074	8.523	Δp_c	1386	19867	3930	7125	4652
				Δp_r		41	41	41	41
				Δp_t		19908	3972	7166	4693
Deodorized oil	879.2	0.0116	2.713	Δp_c	28	9226	2224	3120	4422
				Δp_r		5	5	5	5
				Δp_t		9231	2229	3125	4426
Water	986.75	0.00074	9.410	Δp_c	1530	23635	4691	8430	5590
				Δp_r		50	50	50	50
				Δp_t		23685	4741	8481	5641

In the PHE #6, the pressure drop calculated with Kumar correlation is higher than after the use of other methods, and all the other considerations for PHE# 3 and #5 (oil-water) are valid for PHE#6.

To compare all the pressure drop values obtained by applying different methods, the results of calculations with Buonopane & Troupe correlation were taken as a reference and relative errors to this were calculated.

The relative error is calculated with Eq. 12:

$$relative\ error = \frac{\Delta p_x - \Delta p_{Buonopane}}{\Delta p_{Buonopane}} \times 100\ [\%] \quad (12)$$

The comparison was made only for liquid as a working fluid, because the original correlations were worked out on experimental data on liquids. Results are presented in Table 7:

Table 7. Average relative errors of pressure drop values calculated with different methods compared with those obtained with Buonopane & Troupe method, %.

PHE #	Kumar method	Mulley method	Bond I method
1	+136.5	- 2.0	-41.7
2	+114.0	-36.4	-37.7
3	+183.8	-29.4	-35.9
4	+171.63	-9.0	-35.7
5	+176.32	+16.3	-38.2
6	+191.01	+11.7	-36.1

The pressure drop values calculated with Mulley relationship and Buonopane & Troupe correlation were close and also Bond's equation gave results close to the previous but systematically underestimated. Kumar correlation gave results far from all the others and its application will lead to oversize.

Following this comparative study we recommend the relationships of Mulley and that of Buonopane to be used for the estimation of pressure drop in gasket plate heat exchangers. The Kumar correlation should be applied with caution since it results in oversizing.

5. Conclusions

Different models developed by Kumar, Mulley, Bond and Buonopane & Troupe were applied in industrial conditions on six PHEs in an industrial plant, in different size and working with different fluids (oils with changing properties, cooling water and condensing steam).

The pressure drop values calculated with Mulley relationship and Buonopane correlation were very close and also Bond's equation gave results close to the previous but slightly underestimated. Kumar correlation gave results far from all the others and its application will lead to oversize.

Following this comparative study we recommend the relationships of Mulley and Buonopane & Troupe for the estimation of pressure drop in gasket plate heat exchangers. The Kumar correlation should be applied with caution since it results in oversizing.

These correlations wouldn't be considered for the calculation of pressure drop on condensing steam circuits since they weren't worked out for this type of fluid.

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