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Loss coefficients of ice slurry in sudden pipe contractions

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Abstract In this paper, flow systems which are commonly used in fittings elements such as contractions in ice slurry pipelines, are experimentally investigated. In the study reported in this paper, the consideration was given to the specific features of the ice slurry flow in which the flow behaviour depends mainly on the volume fraction of solid particles. The results of the experimental studies on the flow resistance, presented herein, enabled to determine the loss coefficient during the ice slurry flow through the sudden pipe contraction. The mass fraction of solid particles in the slurry ranged from 5 to 30%. The experimental studies were conducted on a few variants of the most common contractions of copper pipes: 28/22 mm, 28/18 mm, 28/15 mm, 22/18 mm, 22/15 mm and 18/15 mm. The recommended (with respect to minimal flow resistance) range of the Reynolds number (Re about 3000–4000) for the ice slurry flow through sudden contractions was presented in this paper.

Keywords: Ice slurry flow; Flow resistance; Local loss coefficient; Pressure losses in contraction

Nomenclature

D	–	internal pipe diameter, m
g	–	gravitational acceleration, m/s^2
k_{CON}	–	loss coefficient in contraction
K	–	fluid consistency index, Pa s^n
K^*	–	apparent fluid consistency index, Pa s$^{n^*}$

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n	–	flow behaviour index
n^*	–	apparent flow behaviour index
p	–	pressure, Pa
Re	–	Reynolds number
Re_{MR}	–	Metzner & Reed Reynolds number
V	–	average velocity, m/s
x_S	–	mass fraction of ice, %

Greek symbols

α	–	kinetic energy correction factor
β	–	contraction ratio, D_2/D_1
Δ	–	increment
μ	–	dynamic viscosity, Pa s
μ_p	–	elastic viscosity, Pa s
ρ	–	fluid or slurry density, kg m^{-3}
τ_P	–	yield stress, Pa

Subscripts

1	–	upstream of contraction
2	–	downstream of contraction
calc	–	calculated
CON	–	contraction
exp	–	experiment

1 Introduction

Due to the adverse environmental effects caused by some refrigerants commonly used in the air-conditioning and cooling industry, efforts are still underway to find alternative solutions (e.g. intermediate cooling systems) with new, secondary fluids that would be safer for the ozone layer and would not increase the greenhouse effect. There is still a conventional refrigerant in intermediate cooling systems but its quantity is significantly reduced. Secondary proecological fluids, such as water and water solutions are more frequently used nowadays.

Ice slurry belongs to the group of new ecological coolants applied in intermediate cooling systems. It is the mixture of the basic liquid (which could even be water) and the solid particles with the dimensions up to 0.5 mm. Due to such advantages of this refrigerant as showing no adverse environmental effects, having perfect thermal qualities (high thermal capacity, high coefficient of heat transfer, high heat capacity) ice slurry can be used as a direct cooling medium or a medium in which cold is accumulated. First ice slurry systems were built at the beginning of the eighties of last century.

However, the commercial application of this technology can be dated to the nineties (for instance in Germany, Switzerland, Austria, Columbia and Singapore). At present this cooling medium is frequently used to cool down the air conditioning systems of office buildings and hotels as well as in the mine's air conditioning systems. The usage of this cooling medium can also be noticed in supermarkets in refrigerators, refrigerated counters, or food store cold rooms. It is also used in the petrochemical industry, medical engineering, and fire-fighting engineering [1]. Other applications of the ice slurry are still not discovered. It is known, that even due to the heat of the phase change, ice slurry preserve the constant or nearly constant temperature during the heat accumulation (ice slurry made on the basis of water and admixtures lowering the freezing point of water). Therefore it can be used in indirect and direct systems (slurry collecting heat from the primary coolant) to the processes requiring the preservation of the constant and equal temperature during the cooling process of the full section of the cooled solid.

The flow behaviour of ice slurry depends to a large extent on the volume fraction of solid particles [2]:

- with the content of solid particles up to 20% it is a fluid showing the flow behaviour of pure water,
- with the content of solid particles from the range 20%–40% the mixture is still fluid, yet of much higher viscosity than water,
- with the content of solid particles over 40% the mixture looks like wet snow, and due to the transport difficulties it is not used in refrigerating engineering,
- with the content of solid particles of about 90% the mixture is treated as simple ice.

Favourable behaviour of flow resistance are a great advantage of ice slurry (in optimal flow conditions). The mixture can be considered as the so called Bingham fluid [3,4].

Apart from the advantages presented above, ice slurry has its disadvantages. One of them is a tendency of ice agglomerating in a tank, and what follows, the necessity of taking care of the homogenization of the mixture. Such disadvantage can be eliminated by assembling a special stirrer in the ice tank that would provide unification of the mixture ratio in each location of the tank. It enables to supply the exchanger with the mixture of the uniform composition. The shape of the pipelines is of significance. One cannot permit of resting the ice slurry in one section of the pipeline for a longer time, as it would result in the stratification of ice solid particles in the liquid. The cause of such phenomena is the significant difference of densities of the solution and the ice solid particles. The difference arises from the fact that only the water freezes; therefore the alteration of the remaining liquid concentration ensues. Furthermore, due to the physical properties, the volume of ice and the volume of the water from the ice differ. Such situation follows from the fact that water belongs to the group of substances, which enlarge their volume during the solidification. After a long period of time, the stratification of the mixture can cause the flow blockage in the pipeline. The same phenomena can proceed in the three-way pipes which are vertically installed. Ice solid particles can accumulate in the branching-out ducts and result in the flow blockage of this duct. Therefore in such systems branches should be designed horizontally or downwards.

In the subject literature one can find publications dealing with the frictional losses of ice slurry in the straight sections of the pipeline of the circular cross-section, the frictional losses in the slit pipes, or the local losses in the bends and elbows of a circular cross-section [4]. There is still insufficiency of studies on the remaining parts of the fittings, such as ball valves, poppet and control valves, reductions, three-way pipes, and distributors. The common usage of the ice slurry is conditioned by the knowledge of the flow resistances in every element of the pipeline.

2 Methodology of experimental studies

The subject of the study, presented in this paper, are the flow processes occurring in the commonly-used elements of the fittings such as sudden pipe contractions in the pipeline with the flow of ice slurry. In the results of the experimental studies, specific flow behaviour of the slurry, which can be treated as a pseudoplastic non-Newtonian liquid with the qualities of the Bingham liquid, were taken into consideration.

During the preliminary experimental studies [2], one can observe the intrinsic growth of the volumetric flow rate of the ice slurry flowing in the system. This effect occurs till the resistance curves' of the carrying fluid are crossed by the curves of the ice slurry resistance (with the content of solid particles over 20% and high flow velocities). The verification of this phenomenon was conducted in several various ice slurry distribution systems. It was observed that the drop of the flow resistance in all the systems commences below −6.0 °C, i.e. with the content of solid particles over 20%. The relative extremum (minimum) occurs at about −7.1 °C. Despite the fact that such effect proceeds similarly in various ice slurry systems, the scale of this phenomenon strongly depends on the type of the elements of the fittings, such as straight sections, reductions, three-way pipes, valves, dividers, etc., which are used in a given system. Therefore the knowledge about the friction losses (already presented in the literature) and the local losses of the ice slurry in fittings elements is required.

Experimentally determining the flow resistances in pipe contraction and the local loss coefficient took place by measuring of the pressure drop in front of and behind the element. The gauging sections should be placed in distances that are large enough so that their velocity profiles are fully developed and the results of the measurement are not disturbed by the transient phenomena in the recirculation and stagnation sections. The distances of the pipeline in front of and behind the obstacle which are required to obtain the fully developed velocity can be found in the literature [4].

The experimental data are usually presented as plots of the loss coefficient versus Reynolds number, which best describes viscous properties of the fluid. For ice slurry Metzner & Reed Reynolds (Re_{MR}) number will be used [6–8]. The Reynolds number is defined as (1):

$$\mathrm{Re}_{MR} = \frac{8\rho V^2}{K^* \left(\frac{8V}{D}\right)^{n^*}} \,. \tag{1}$$

The loss coefficient for sudden contractions is presented by correlation (2), which takes into consideration the excess pressure drop and kinetic energy correction factors (α). The loss coefficient is defined as [8,9]:

$$k_{CON} = \frac{\dfrac{\Delta p_{CON}}{\rho g} + \dfrac{\alpha_1 V_1^2 - \alpha_2 V_2^2}{2g}}{\dfrac{V_2^2}{2g}} \,. \tag{2}$$

The experimental studies were conducted on six different sudden pipe contractions with the contraction ratios shown in Tab. 1.

Ice slurry with a different ice concentration, x_S (5, 10, 15, 20, 25 and 30%) and the average size of ice crystals (width/lenght) 0.1/0.15 mm was used in the experimental studies. The mean flow velocity of ice slurry in the

Table 1. Contraction ratios and internal diameter behind the contractions.

Contraction ratio, $\beta = D_2/D_1$	0.813	0.800	0.769	0.650	0.615	0.500
Internal diameter D_2 [mm]	13	16	20	13	16	13

studies ranged from 0.1 to 4.7 m/s. The schematic diagram of experimental test stand is shown in Fig. 1.

For the purposes of the study, ice slurry with a given volume fraction of solid particles first had to be generated and accumulated in the storage tank. To unify the composition of the ice slurry, it was necessary to use the stirrer in the storage tank as well as the system preventing the effect of aeration. Moreover, the test stand was equipped with the temperature control system for the slurry (accuracy of measurement: 0.05 K), multipoint system controlling and recording the pressure and the differential pressure (measuring range 1, 6, 12, 32, 130 kPa, accuracy of measurement: 0.2%), two Coriolis mass flowmeters (accuracy of measurement: 0.1%), and the system controlling the volume fraction of solid particles in the slurry. Pressure taps and differential pressure transducers were used in the stand both, in the measurements of the contractions and the resistance measurements in straight pipes. All the measuring devices used in the stand were calibrated and received calibration certificates. The flow control pipe was used for the transmission of the ice slurry from the storage tank to the measuring section. The whole test stand, and especially the measuring section, were insulated with the refrigerating insulation. It is not only important due to the reduction of energy losses, but mostly because of preserving the constant mixture ratio during the studies. Thanks to that it was possible to avoid the melting of ice solid particles and not to cause interferences in the testing results. The measuring position was favorably tested by using a carrying fluid without ice solid particles.

3 Experimental studies

To determine the loss coefficient it is necessary to know the Coriolis coefficients for respective profiles. In the literature, one can find a few methods for determining such values. Dependences given by Fester *et al.* [8]

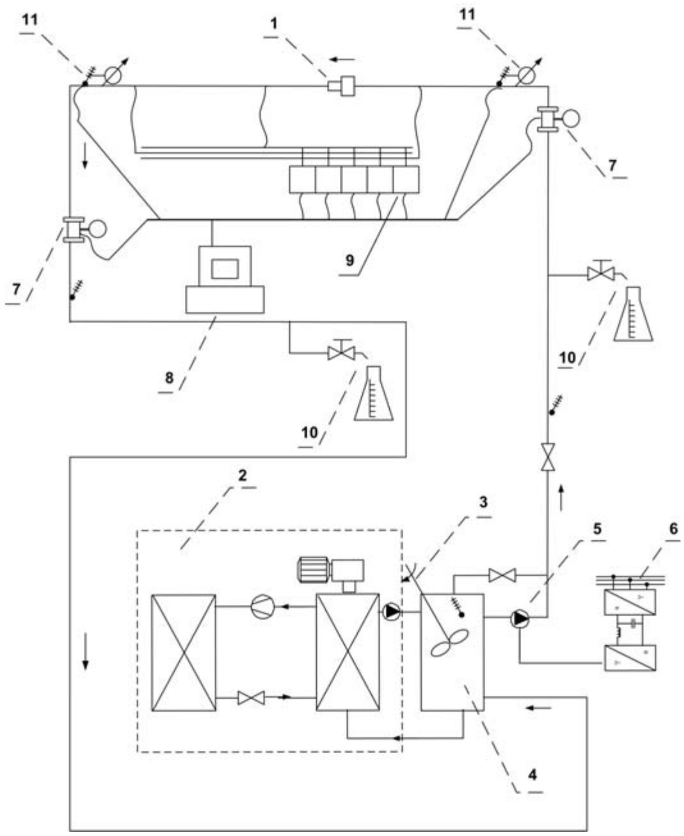

Figure 1. Schematic diagram of experimental test stand: 1 – contraction, 2 – ice slurry generator, 3 – mixer, 4 – storage tank, 5 – main pump, 6 – main pump inverter, 7 - mass flow-meter, 8 – data collecting, 9 – multipoint measurement of pressure drop, 10 – measurement and control of ice volume fraction, 11 – measurement of temperature and pressure.

and Szewczyk [10] (modified later by Strzelecka and Jeżowiecka-Kabsh [11]) were used in this paper. Such dependences were revised by theoretical calculations based on the analysis of two-dimensional velocity profiles of the ice slurry presented in Niezgoda-Żelasko papers [3,4] and own complementary calculations. The calculations revealed that for the ice slurry with the content of ice solid particles up to 20% Coriolis coefficients well describes the modified (by Strzelecka and Jeżowiecka-Kabsh) Szewczyk's dependence:

$$\alpha = 1 + 105\left(\frac{10}{\ln^2 \mathrm{Re}}\right)^3 - 11.88\left(\frac{10}{\ln^2 \mathrm{Re}}\right)^2 + 1.208\left(\frac{10}{\ln^2 \mathrm{Re}}\right) , \qquad (3)$$

for non-Newtonian liquids (with the maximum value of 2). For the slurry with the content of ice solid particles over 20% one can ascribe the dependence given in [8] for non-Newtonian liquids:

$$\alpha = \frac{3\,(3n+1)^2}{(2n+1)\,(5n+3)} \, . \qquad (4)$$

The flow behaviour index value for all calculation of the ice slurry flow ranged from 0.25 to 1.0.

The knowledge about some of the qualities of the ice slurry was necessary to make the essential calculations. In the literature, one can find a few authors examining the qualities of the ice slurry and some other slurries. Qualities of this coolant given by the authors often differ between themselves. In this paper, the qualities given by Melindner [12] were used and later revised and supplemented with the plastic viscosity μ_P and the yield shear stress τ_P [4]. In the experimental studies aimed to determine the local loss, the losses of the friction in the straight sections of the pipeline with the diameters of ϕ15 mm, ϕ18 mm, ϕ22 mm and ϕ28 mm were also determined.

The results of the studies on the loss coefficient of the ice slurry flowing through the sudden pipe contractions with a given contraction ratios versus Reynolds number according to Metzner & Reed are shown in diagrams 2–7. In the turbulent range, measured values of the loss coefficient show similar values to non-Newtonian liquids (e.g. water), which can be calculated according to the dependence [13,14,11]:

$$k = 0.5\left(1 - \beta^2\right) \, . \qquad (5)$$

The consistence of the value of the loss coefficient of the non-Newtonian liquid and the loss coefficient of the Newtonian liquid in the turbulent flow is also confirmed by other papers [6,4,8]. Table 2 shows the comparison of the mean values of the loss coefficient in the turbulent range obtained in the experimental studies and the results of the calculations on the basis of the dependence (5).

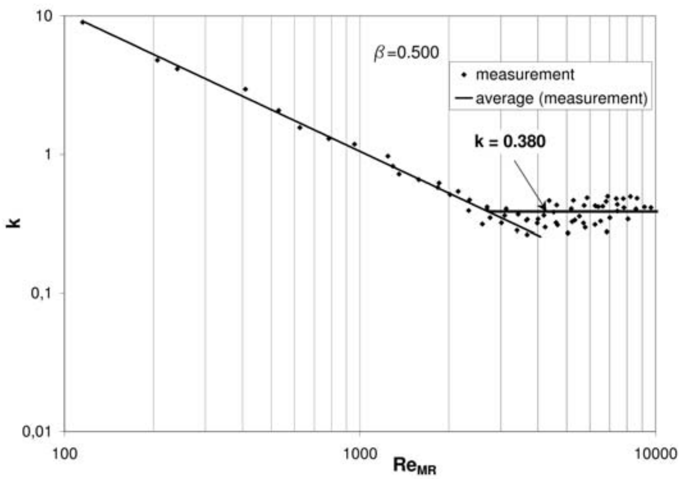

Figure 2. The results of experimental studies on the loss coefficient for the ice slurry flow in pipe sudden contraction versus Reynolds number, $\beta = 0.500$.

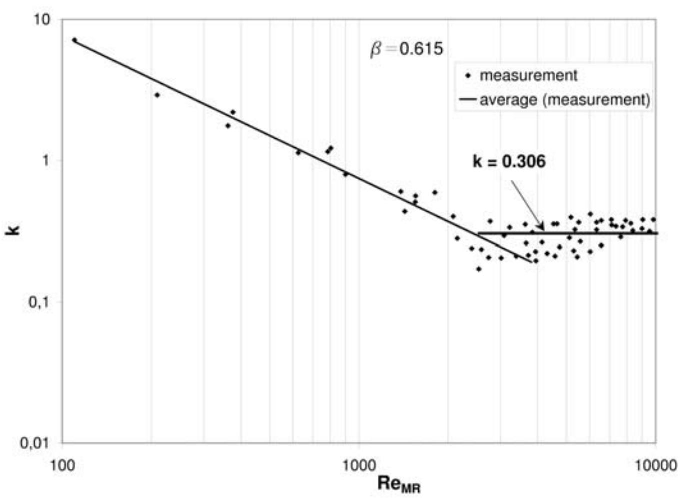

Figure 3. The results of experimental studies on the loss coefficient for the ice slurry flow in pipe sudden contraction versus Reynolds number, $\beta = 0.615$.

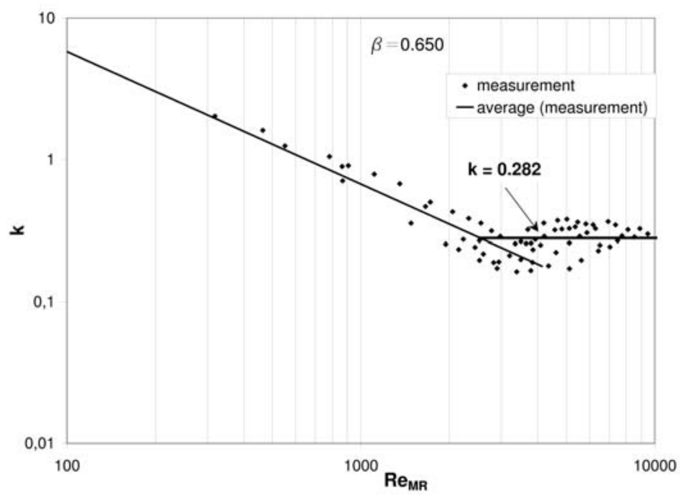

Figure 4. The results of experimental studies on the loss coefficient for the ice slurry flow in sudden pipe contraction versus Reynolds number, $\beta = 0.650$.

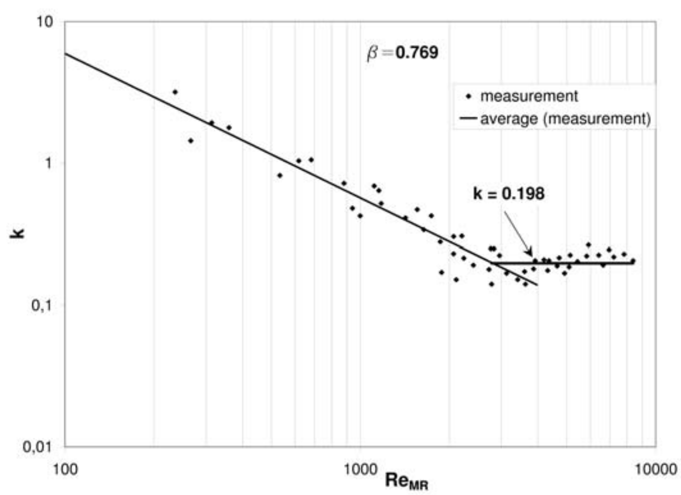

Figure 5. The results of experimental studies on the loss coefficient for the ice slurry flow in sudden pipe contraction versus Reynolds number, $\beta = 0.769$.

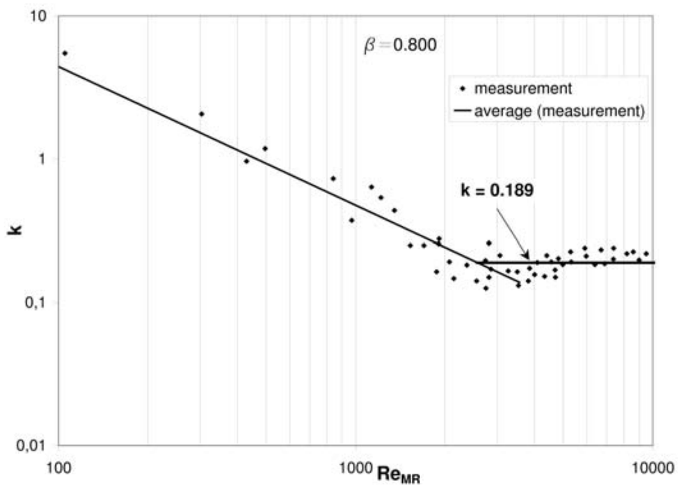

Figure 6. The results of experimental studies on the loss coefficient for the ice slurry flow in sudden pipe contraction versus Reynolds number, $\beta = 0.800$.

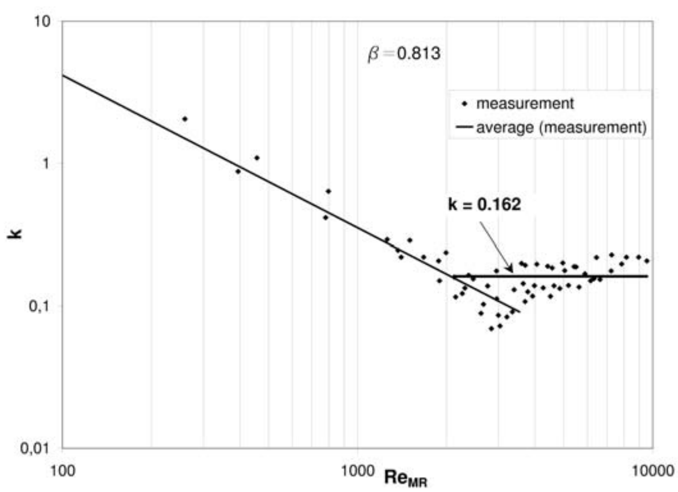

Figure 7. The results of experimental studies on the loss coefficient for the ice slurry flow in sudden pipe contraction versus Reynolds number, $\beta = 0.813$.

Table 2. Local loss coefficients in turbulent flow in contractions obtained from measurement and calculation (5).

Contraction ratio, $\beta = D_2/D_1$	0.813	0.800	0.769	0.650	0.615	0.500
k_{exp}	0.162	0.189	0.198	0.282	0.306	0.380
k_{calc}	0.170	0.180	0.204	0.289	0.311	0.375

4 Conclusions

1. The application of ice slurry as the intermediary agent results in many benefits, such as for instance decreasing of the degradation of the atmosphere due to limiting the usage of harmful freons, increasing the heat penetration factor which enables to reduce the heat exchange surface, the pump capacities and pipeline diameters as compared to the brine systems. It also reduces the agent flow resistance in the system.

2. In the literature there are no theoretical dependences supported by the experimental studies that would concern determining the loss coefficient of the ice slurry flowing through the sudden pipe contractions.

3. The average loss coefficients of the ice slurry obtained during the studies conducted in the turbulent flow are very similar to those calculated on the basis of the dependence (5) as for Newtonian liquids.

4. It is not recommended to use the flow velocity of the ice slurry lower than 0.1 m/s in order to avoid the flowing problems of that mixture (autogenous flow blocking).

5. During designing the ice slurry systems, one should select, if at all possible, such diameters of the pipeline, flow velocity, and parameters of the mixture that would enable to obtain the minimum loss coefficient which mostly amounts to the Reynolds number range Re_{MR} = 3000–4000. It would enable to limit the flow resistances in the system and reduce the operating costs. On the other hand it should be marked that reducing the Reynolds number can influence decreasing of the heat transfer coefficient of the ice slurry.

6. Further studies on the determination of the resistance coefficient in the remaining fittings elements of the pipeline are necessary as well

as the further theoretical studies intended to determine the theoretical relations to calculate the local resistance coefficient (especially in laminar flow) in all the fittings elements in the pipeline (on the basis of the experimental studies) and to elaborate the calculation pattern of the entire ice slurry system.

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