Efficiency and Effectiveness
of High-Pressure Milk Homogenization

by

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I wish to thank everybody.

Abstract

Milk high-pressure homogenization is studied as an example of an inefficient and empirical process. Energy efficiency is defined as the theoretical efficiency, while any other comparative, practical evaluation of homogenizer performance is termed "effectiveness".

The theoretical minimum energy required for milk homogenization is found and used to determine the theoretical efficiency, found to be about 0.01%. With a new defined effectiveness, the comparison of seven functions relating pressure of homogenization to final fat globule diameter is done; and lastly, an attempt to predict the rate of creaming in homogenized milk shows the difficulties of simulation of food materials. This same difficulty (the complexity of foods and the insufficient knowledge we have about their properties) is said to be preventing the progress of Food Engineering as a discipline of the applied sciences.

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Introduction

Homogenization is a process to make food emulsions stable. In high-pressure homogenization particularly, the fluid product is forced through a narrow slit (~30 μm) at very high pressures (500 to 5,000 psi). The result is an increment in the total area of interface between the disperse and continuous media of the emulsion--effected by reducing the size of the globules of the disperse medium--and consequently the stabilization, or homogenization, of the emulsion.

Milk, the most important homogenized food product, is an emulsion of milk fat in the liquid milk-serum, where milk fat constitutes about five percent of the total volume.

In this study, an evaluation of the performance of milk high-pressure homogenization, in the form of efficiency and effectiveness calculations, is intended. However, the ultimate objective is not merely to show high-pressure homogenization as an efficient or inefficient process, but to point out a major, general problem in the field of food engineering: to make clear that the problem-solving approach of the engineer, when dealing with food products and the transformations that processing induces in these products, has been, and still is, less scientific than empirical.

Homogenization <u>is</u> an empirical process. A valve was invented by Gaulin in 1898 (the homogenizer valve, shown in Figure 1) which, when milk was forced through it, did the job satisfactorily. Gaulin's same valve constitutes the heart of the high-pressure homogenizer today; but no one, after many years of formulation and refusal of theories, has yet been able to explain why, or how, do milk fat globules break to a smaller size when passing through the microscopic dimensions of the valve. (For reviews of the theories of homogenization see references (9), (11), and (7)).

In this sense, then, homogenization is empirical: a process that induced the right changes in the material before we could explain it.

Also, from the fact that milk fat constitutes only five percent of the total volume of milk (less than five percent of the total weight), we can infer that a process like milk high-pressure homogenization, intended to induce a change in the fat globules only, but which subjects the totality of the milk volume to the same high-pressure treatment, is inefficient. Indeed, homogenization is inefficient. Mulder and Walstra (7) put it simply: "it consumes much energy and requires costly machinery."

Milk high-pressure homogenization is, then, empirical and inefficient. But, how inefficient is it? Can we quantify it?, and what are the consequences of its being empirical?

Attempting to answer these questions, this report has been divided into three main sections:

1. Definition of a theoretical efficiency as the ratio of the minimal energy needed to accomplish homogenization over the actual energy used.

2. Definition of an effectiveness as a ratio of final over initial fat-globule average diameters, and its application for comparing the performance of different homogenizers.
3. An attempt to relate quantitatively pressure of homogenization, and the effectiveness defined in 2, to the phenomenon of gravity creaming (fat rising to the top of a volume of milk due to a density difference).

Two terms must be clearly understood before presenting the results: In this thesis, the word efficiency stands for an absolute evaluation of the performance of a machine, a ratio of the theoretical minimum energy needed to induce the desired change in the product over the actual energy that is used. The word effectiveness is used for any evaluation of the performance of a machine done in relative terms, always aiming at checking the quality of one individual final product as compared to other final products. An effectiveness is any comparative evaluation of the performance of a machine while efficiency is the theoretical one, based on energy ratios.

Literature Review

Three approaches have been followed in the past to define and determine homogenization effectiveness.

The first approach uses the speed of fat rise (creaming) as the parameter for comparison: well homogenized milk will cream more slowly than poorly homogenized milk. The basis for this assumption is Stokes' law (see equation 19) which predicts slower rise for smaller fat globules. An example of this approach is the definition given in 1942 by the U.S. Public Health Service which states that:

> "homogenized milk is milk which has been treated in such a manner as to insure break up of the fat globules to such an extent that after 48 hours storage no visible cream separation occurs on the milk, and the fat percentage of the top 100 cc. of milk in a quart bottle, or of proportinate volumes . . . does not differ by more than 10 percent of itself from the fat percentage of the remaining milk . . ." (4).

A second, more recent approach, is based on the degree of fat dispersion. When homogenization breaks the fat globules from an initial size down to a smaller final average size, fractions of the number of globules end up larger and smaller than the average size. The spread, or deviation from the average size (and the percent by weight of fat in the globules corresponding to this spread), constitutes the degree of fat dispersion.

Walstra (cited in (7), pp. 171, 172) has determined that the degree of fat dispersion is proportional to the pressure of homogenization (see Figure 2). And Lukyanov and Eremina (5) have given a practical equation for the degree of fat dispersion with increasing pressure:

$$E = 16.36 \sqrt{P} + 8.79\%$$

where E is in percent and P in Mega Pascals.

The third approach evaluates homogenization as a function of the final average diameter of the fat globules.

The method of Farrall (3) follows a laboratory procedure of microscopic examination to determine the number of fat globules per unit volume of milk and their sizes. The procedure yields a number: the Farrall index.

But the most important application of the concept of globule size reduction with homogenization has been in the study of the many parameters that have an effect on homogenization. Among these parameters the most important are the following:

pressure
volumetric flow rate
velocity drop across the valve
valve design, make, and wear
whether one or multi-stage homogenization
valve-slit clearance
vibrations of the valve
evenness of pumping
temperature and temperature-related
  milk properties (i.e., viscosity)
fat content of milk.

Phipps and Goulden (10) have studied the joint effect of flow rate, temperature and milk fat content. Surkov and Komlyakov (14) have given equations for the performance of single-stage and multi-stage homogenizers; and in (13) Surkov and Fofanov subjected the homogenizer valve to high frequency mechanical vibrations obtaining a considerable increase in efficiency. Phipps (8) has studied homogenizer mechanics and the effect of the valve-slit clearance on the effectiveness of homogenization.

Mulder and Walstra (7) and Rees (12) give knowledgeable reviews of the entire subject.

Results

I. Homogenization Efficiency

a. Rittinger's law

In 1859, Rittinger developed the following theoretical equation (known as Rittinger's law) for the energy needed in the comminution of solid particles:

$$\frac{dE}{dD} = -K \frac{1}{D^2} \qquad 1$$

or

$$E = K\left(\frac{1}{D_2} - \frac{1}{D_1}\right) \qquad 2$$

where D is the diameter of the particles, E the energy used, and K a constant.

Rittinger noted that the amount of energy needed to reduce the average particle size was directly proportional to the change in total surface area.

As will be seen, this same principle holds for the breaking of fat globules in milk homogenization.

b. Minimum energy for homogenization

The minimum energy required to homogenize a volume of milk would be the energy needed to reduce the average size of a definite number of globules from an initial to a final, smaller diameter ($d_1 > d_2$);

from an initial to a final, larger total surface area ($A_1 < A_2$); the total volume of fat remaining constant. Put as an expression:

$$\begin{aligned} Eg &= \Delta S \\ &= S_2 - S_1 \end{aligned} \qquad 3$$

where ΔS is the change in interfacial free energy due to the increase in total interfacial area between fat and milk serum when the reduction in diameter occurs. But

$$S = Ia \qquad 4$$

where I is the average interfacial free energy for a milk fat-milk serum interface (5 ergs per square centimeter), and "a" is the average specific surface of fat in whole milk (about 800 square centimeters per mililiter of milk) - (both values from reference 7). So

$$S_2 - S_1 = N(Ia) - (Ia) \qquad 5$$

where N is the number of times the total area of fat-serum interface increases with homogenization (4 to 8 times normally). N is also d_1/d_2; this is true because the average diameter of a number of fat globules is defined as a volume to surface ratio (see reference 7, p. 57), from which the definition of total surface area of fat-serum interface is:

$$a = \frac{6\phi}{d} \qquad 6$$

where ϕ is the volume fraction of fat.

So

$$N = \frac{a_2}{a_1} = \frac{6\phi/d_2}{6\phi/d_1} = \frac{d_1}{d_2} \qquad 7$$

and equation 5 becomes

$$\begin{aligned} \Delta S &= S_2 - S_1 \\ &= NIa - Ia \\ &= \frac{d_1}{d_2} Ia - Ia \\ &= Ia(\frac{d_1}{d_2} - 1) \qquad 8 \end{aligned}$$

Equation 8 gives the minimum energy required to homogenize for any deduction in diameter. It gives a theoretical value probably impossible to reproduce.

Notice that equation 8 can be rearranged in the form of Rittinger's law:

$$\frac{\Delta S}{\Delta d} = - Ia\frac{1}{d_2} \qquad 9$$

(consider, in equation 2, D_1 a constant). This makes homogenization theoretically akin to a solid particle comminution process.

c. Theoretical efficiency

Efficiency was defined before as the ratio of the theoretical minimum energy needed to induce a change in the product over the actual energy used. For homogenization,

$$\text{efficiency} = \frac{\Delta S}{\Delta P/\rho} \times 100 \qquad 10$$

where ΔS is given by equation 8 and $\Delta P/\rho$ is the homogenizer pump pressure head. With equation 8, equation 10 becomes:

$$\text{efficiency} = \frac{Ia\left(\frac{d_1}{d_2} - 1\right)}{\Delta P/\rho} \times 100 \qquad 11$$

Lukyanov and Eremina (5), citing Baranovskij, give the following formula for determining the average diameter of the fat globules after homogenization:

$$d_2 = \frac{3.79}{\sqrt{P}} \qquad 12$$

with d_2 in micrometers and P in Mega Pascals. (any of equations 16 to 18 could have been used instead of 12 but the difference would be small).

Equation 12 into 11:

$$\text{efficiency} = \frac{Ia\left(\frac{d_1\sqrt{P}}{3.79} - 1\right)}{P/\rho} \times 100 \qquad 13$$

where P is being assumed equal to ΔP, the pressure of homogenization.

Equation 13 is the final expression for the theoretical efficiency of homogenization. It is plotted in Figure 3 for different values of P.

II. Homogenizer Effectiveness

a. Effectiveness (defined)

Figure 4 shows a curve of effectiveness, ef., as a function of the average diameter of the fat globules after homogenization, d_2, The shape of the curve was determined arbitrarily from the following observation:

1. the average diameter of the fat globules in non-homogenized milk is about 3.5 micrometers (7)
2. the smallest attainable diameter is about 0.35 micrometers (5)
3. homogenization is said to be "proper" when the average diameter of the fat globules is somewhere below one micrometer (7).

Considering then a homogenization that gives $d_2 = 3.5\ \mu m$ as zero percent effective, one that gives $d_2 = 1\ \mu m$ as 50 percent effective, and one that takes d_2 down to $0.35\ \mu m$ as 100 percent effective, the three main points were determined.

The equation that fits the curve defined in Figure 4 is:

$$\text{effectiveness} = \frac{305.8}{\sqrt[7]{d_2}} - 255 \qquad 14$$

where effectiveness is in percent and d_2 is in micrometers.

b. Comparison of homogenizer performance

Equations 15 to 18 were gathered from the literature. They are all experimentally determined relations between homogenization pressure and the final average diameter of the fat globules. For every equation P is in atmospheres and d in micrometers.

1. Lukyanov and Eremina (5), citing Baranovskij, give

$$d_2 = \frac{11.92}{\sqrt{P}} \qquad 15$$

(this is the same as equation 12 but P is herein). The flow rate is 100 ℓ/hr.

2. Surkov and Komlyakov (14) give

$$\log d_2 = 0.9 - K \log Pe \qquad 16$$

where Pe is the sum of the pressures applied, and

$K = 0.39$ for one-stage homogenization 16(a)

$K = 0.4$ for multi-stage with descending pressure 16(b)

$K = 0.41$ for multi-stage with ascending pressure 16(c)

The flow rate is always 130 ℓ/hr and the pressures, applied to 1 to 7 stages, range from 30 to 300 athmospheres. Milk temperature is 65 C.

3. Phipps, 1975 (8), gives plotted data for a process of 100 ℓ/hr which fits the equation:

$$d_2 = 27.835\ P^{-0.685} \qquad 17(a)$$

and for a process of 30 ℓP/hr which fits:

$$d_2 = 25.51\ P^{-0.685} \qquad 17(b)$$

Milk temperature is 50 C.

4. Phipps, 1978 (9), gives plotted data for a process of 100 ℓ/hr, at 50 C, and with a rounded inlet value. The fitted equation is:

$$d_2 = 57.588^{-0.8} \qquad 18$$

Solving together equation 14 and each of equations 15 to 18 we get the seven functions on top of Table 1. The values obtained in Table 1 are plotted in Figures 5 and 6.

III. Attempts to Simulate Fat Globule Rise and Creaming

The purpose of milk homogenization is to prevent fat rising to the top of the container (creaming). This fact becomes particularly important when dealing with long-life milk products. So, ultimately, every effectiveness defined should aim at evaluating how well did we homogenize; this is, how much fat rise did we get after putting a certain amount of energy into homogenizing.

Stoke's law, for the rate of rise of small spheres in a viscous medium, has been proved by Troy and Sharp (15) to hold for individual fat globules. But it did not reproduce creaming in a whole volume of milk. Stoke's law is

$$v = \frac{g(\rho_m - \rho_f)d^2}{18\ N_m} \qquad 19$$

where v = rate of rise, g = acceleration of gravity, ρ_m = density of milk plasma, ρ_f = density of fat, d = globule diameter, and N_m = viscosity of milk plasma.

Mulder and Walstra (7) give the following statements as prerequisites for the validity of Stoke's law:

> ". . . counterflow of liquid due to the globule movement must be negligible: this is only true for low volume concentrations of globules . . . . . . mutual interaction between globules must be absent . . ."

But there are other factors related to the chemical composition of milk and specially the fat globule membrane--i.e., the polarity of the phospholipid components of the membrane which could have an "anchoring" effect, the fact that homogenization forces some of the plasma proteins into the fat globules making their density higher--that may have a negative effect on rise but of which we know too little to be able to quantify their effect.

Using the U.S. Public Health Service definition of well homogenized milk (see Literature Review, p. 4) and assuming that milk with fat globules of one micrometer average diameter would produce the 10 percent difference in the quart volume at exactly 48 hours, it can be shown that the rate of rise is nearly one thousand times slower than that which Stoke's law would predict for the same diameter.

In reality, milk fat, after homogenization, would seem not to rise at all. Andrews, *et al*. (1) do not mention fat rise in their study of the storage changes in long-life milk products, but give gelation as the determinant of the final limit of storage life.

In conclusion, homogenized milk, because of not well known physical and chemical characteristics of its composition, and because of the un-measurable changes produced in it by homogenization, does not cream--or does it so slowly that its effect is not significant.

Discussion

I. Homogenizer Efficiency

Figure 3, the plot of equation 8 for various pressures, shows a peak value of 0.0085 percent at 5 Mega Pascals. That is the theoretical, total efficiency of homogenization--below 0.01 percent--,showing homogenization as a very inefficient process.

The similarity of homogenization with a solid - particle grinding process was also shown. According to Brennan, et al. (2), efficiencies of 2 percent can be expected for grinding.

If we notice that in homogenization only 5 percent of the volume subjected to the high pressure treatment (fat) requires this treatment, do we approximate homogenization efficiency by saying that it is 0.05 x 2% = 0.1%? 0.1% is still ten times larger than the largest value from equation 8. Where does all the wasted energy go?

Enormous pressure losses due to friction at the homogenizer value result in a significant increase in the temperature of milk, predicted by the equation of Mitten and Preu (6):

$$\Delta T = \frac{P}{42 \rho Cv} \qquad 20$$

where P = pressure of homogenization in athmospheres, Cv = specific heat of the milk (in Cal gm^{-1} C^{-1}), and ρ = milk density.

High pressure is also being used to accelerate greatly the total volume of milk when the liquid is forced through the narrow slit of the valve (280 m/sec for 400 atm pressure, (7)).

And finally, not all of the energy that does work upon the fat globules is used in immediately increasing the total surface area. Much of it is used in deforming the globules up to their elastic limit, where they break.

II. Homogenizer Effectiveness

The following observations are clear from Figures 5 and 6 for the comparison of the seven pressure-diameter functions through the defined effectiveness:

The approximate average pressure corresponding to 50 percent effectiveness is 130 atm or 2,000 psi, a value well within the range of normal milk homogenization. This confirms that the choice of one micrometer as corresponding to 50 percent effectiveness was good, and that equation 11 reproduces actual phenomena reliably.

From comparison of the two equations by Phipps for 100 ℓ/hr and 30 ℓ/hr (17(a) and 17(b)), homogenization at a lower flow rate shows a higher effectiveness.

From the three curves in Figure 6 for equations 16(a), 16(b) and 16(c), representing Surkov and Komlyakov's experiments, multi-stage homogenization with ascending pressure shows a higher effectiveness than multi-stage desending and simple stage homogenization, but the difference is small (5 percent at 400 atm).

III. Fat Globule Rise

The failure of research to give an accurate expression for the rate of rise of fat in milk (due mainly to the many unknowns in the physical and chemical constitution of milk), reveals, together with the fact that homogenization is an empirical process, an important "gap" in the broader field of food engineering.

Foods are complex biological materials--animal or vegetable tissues or secretions, or mixtures of all these. They are also highly variable, milk alone changing from cow to cow due to breed, feed or season. In general, the basic chemistry and physics of foods, complex as they are, have been little studied in the past, and their principles are, in many cases, poorly known.

The engineer who has to process those materials--inducing physical and chemical changes by the application of heat, external forces, or the other means--is forced to be empirical in his approach by the very nature of the materials he works with--foods: un-reproduceable, unmeasurable, never alike. So he is unable to calculate accurately the changes he will induce; or he does not know to what extent to process.

In view of this, it is not unexpected that there are food processing operations that are less than one percent efficient, like homogenization.

And even if considerable effort is being put into studying food materials and their properties, the problem for the engineer is, at present, a valid one.

Food engineering is a field where, most of the times, solutions to real problems are found empirically, following no method, no specialized theory. Without the adequate knowledge of the material with which the food engineer works, his field of activity, as a field of applied science, will not progress. It will not reach the level of a true discipline where the observed phenomena can be reproduced with a certain precision and where the limits to knowledge can be reached, explained, and surmounted to face new limits.

Conclusions

Milk high-pressure homogenization has been found to be less than 0.01 percent energy-efficient; a very inefficient process.

The following equation, defined as homogenization effectiveness, has proved to reproduce well actual data and it can be used to compare the performance of different homogenizers:

$$\text{effectiveness} = \frac{305.8}{\sqrt[7]{d_2}} - 255$$

where d_2 = the average diameter of the fat globules after homogenization.

The rate of rise of fat in homogenized milk is about one thousand times slower than predicted by Stoke's Law.

Neither the basic chemical and physical properties of milk nor the actual changes in these properties induced by homogenization are enough known. These changes being unmeasurable, we cannot quantify them for purposes of design or processing. This is why processes as inefficient as homogenization exist.

Food engineering in general, because it works with complex biological materials, has to rely on an empirical approach to problem solving. More research on the basic properties of foods is needed to make food engineering a more exact field among the applied sciences.

Figure 1. Homogenization process and value

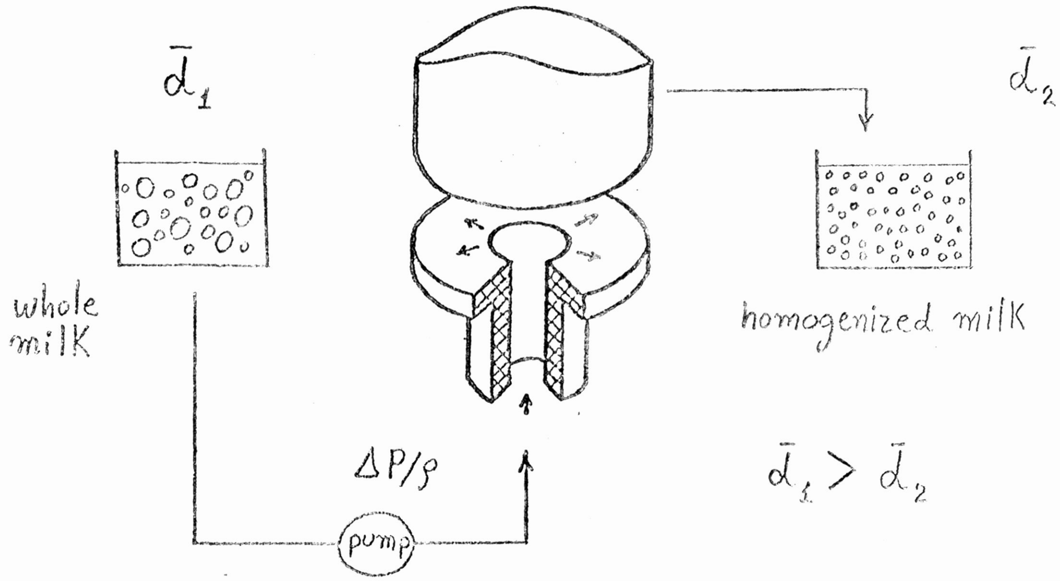
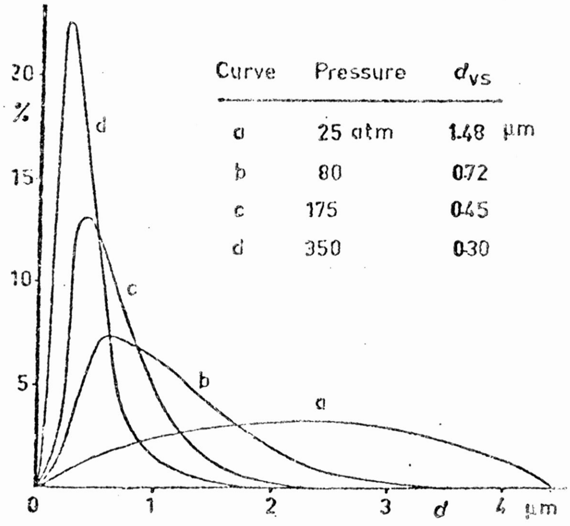
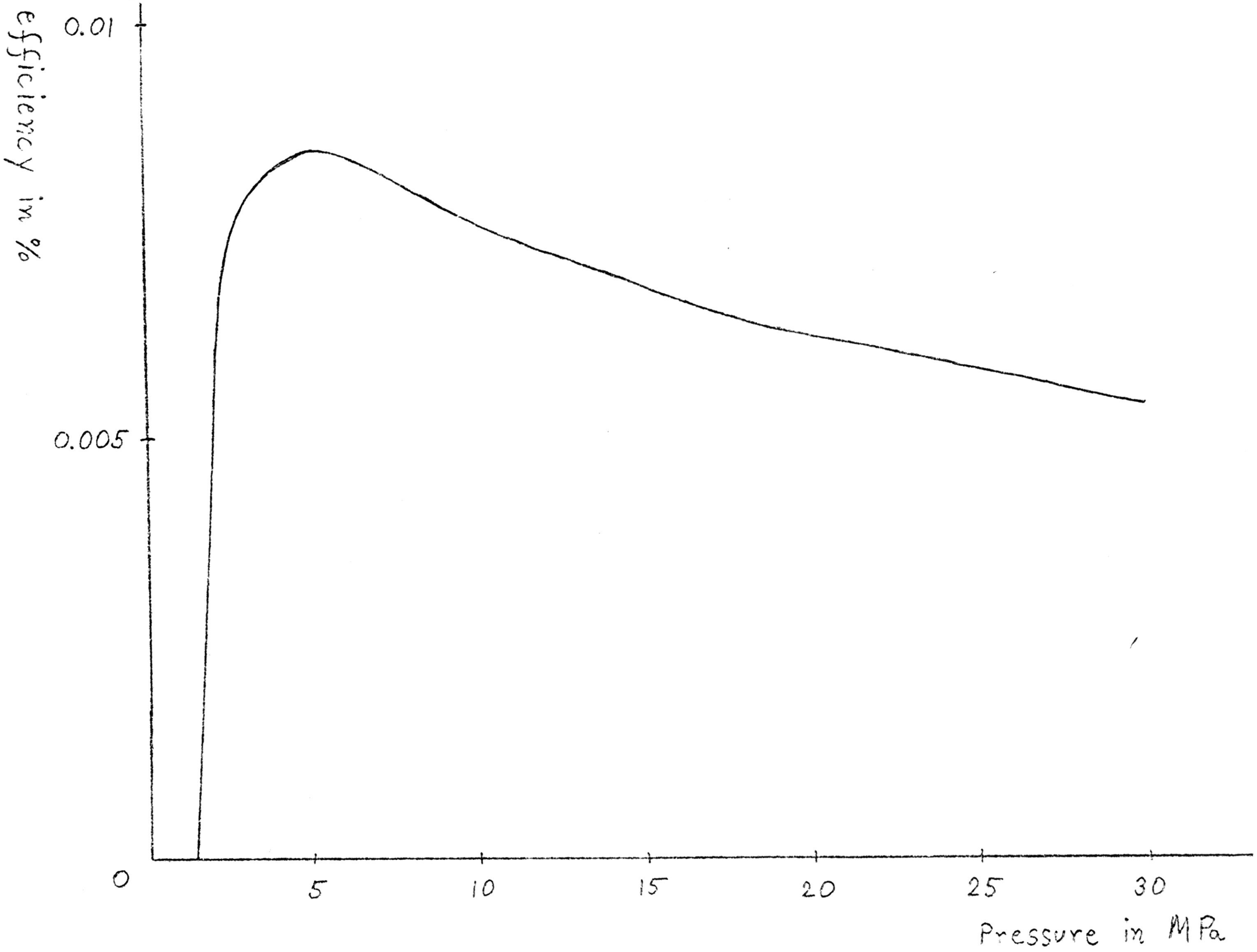


Figure 2. Degree of homogenization (From reference 7, p.172, after Walstra)



Curve	Pressure	d_{vs}
a	25 atm	1.48 µm
b	80	0.72
c	175	0.45
d	350	0.30

Figure 3. Homogenization theoretical efficiency (Equation 13 for pressures 0-30 MPa)



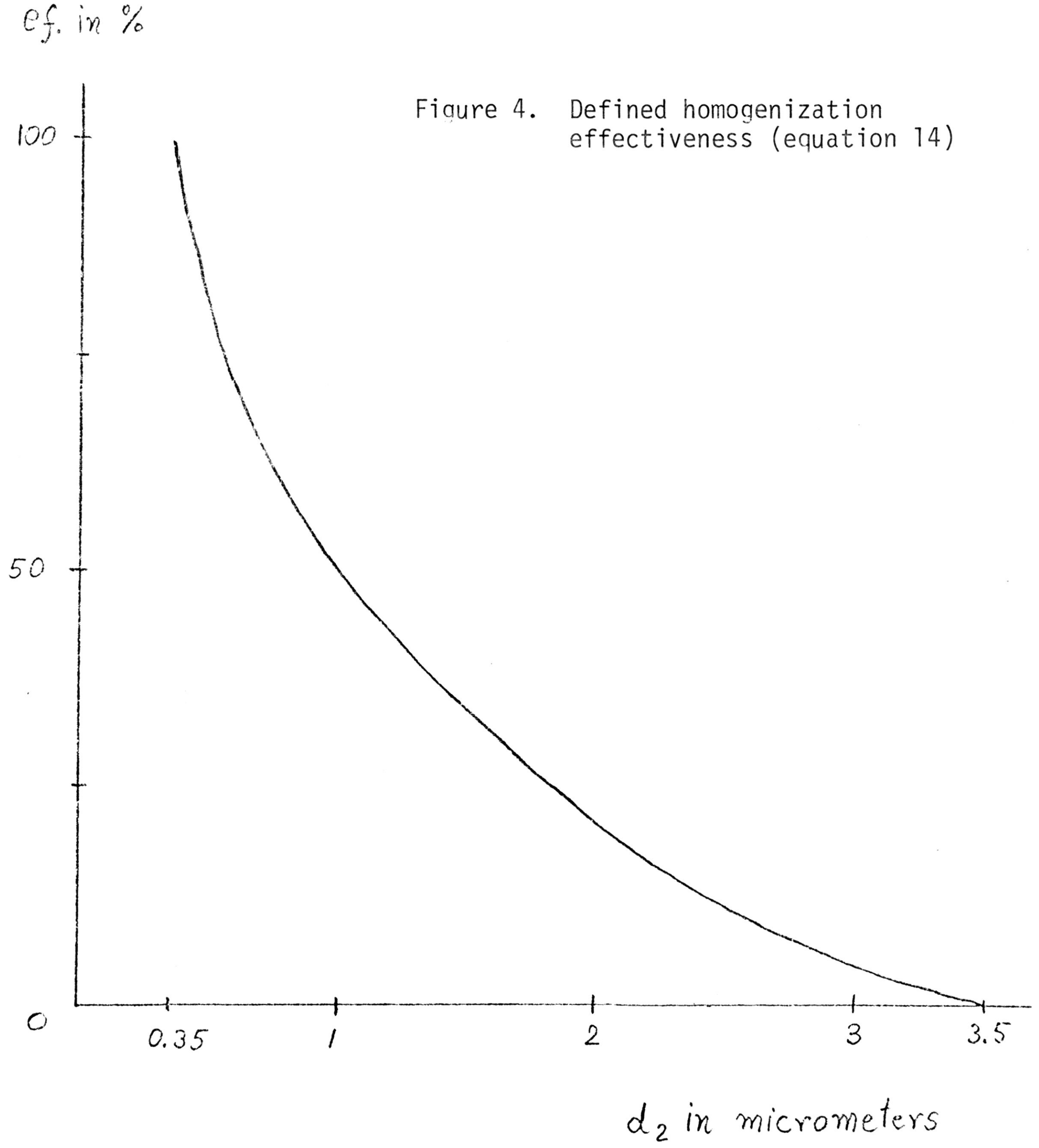


Figure 4. Defined homogenization effectiveness (equation 14)

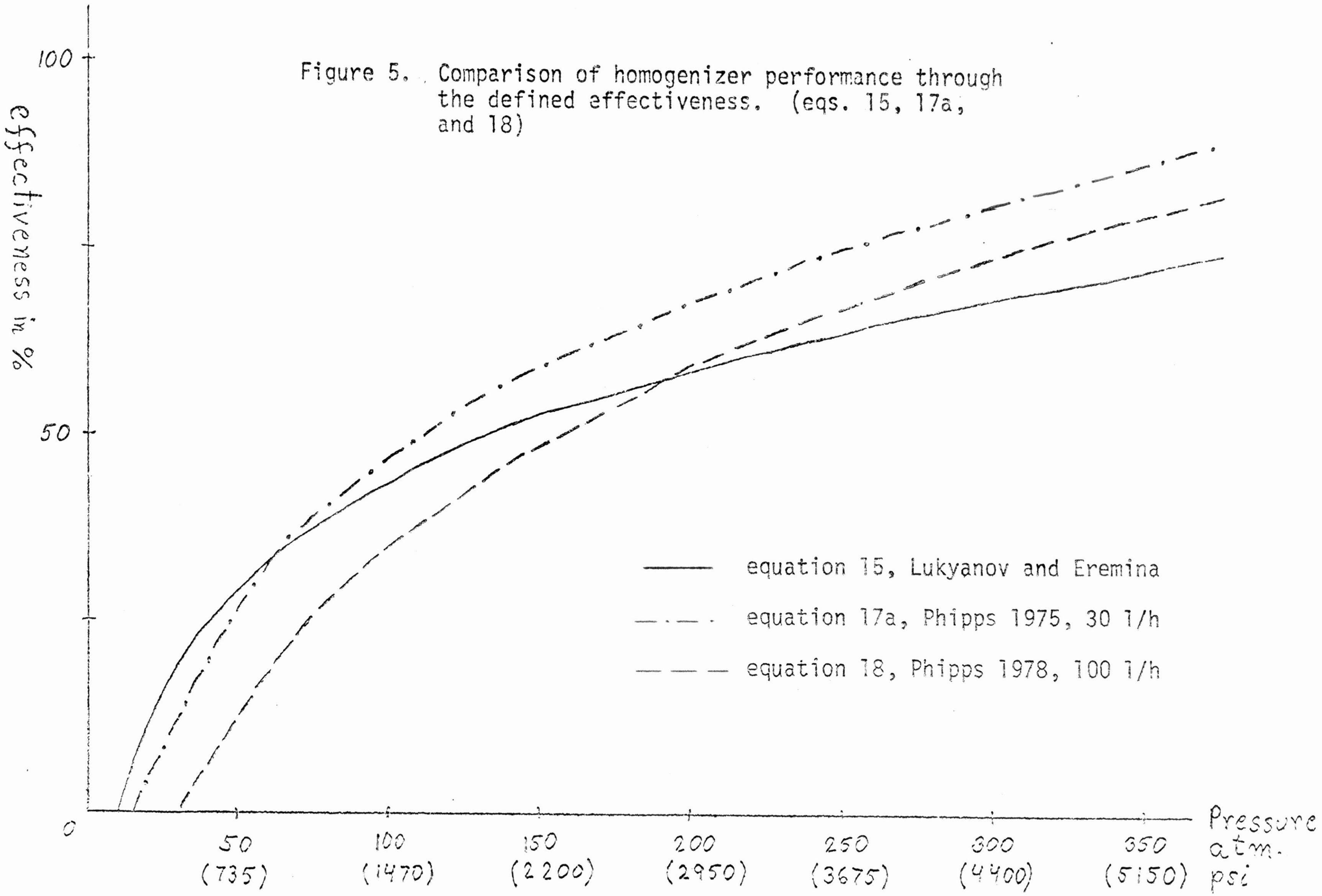


Figure 5. Comparison of homogenizer performance through the defined effectiveness. (eqs. 15, 17a, and 18)

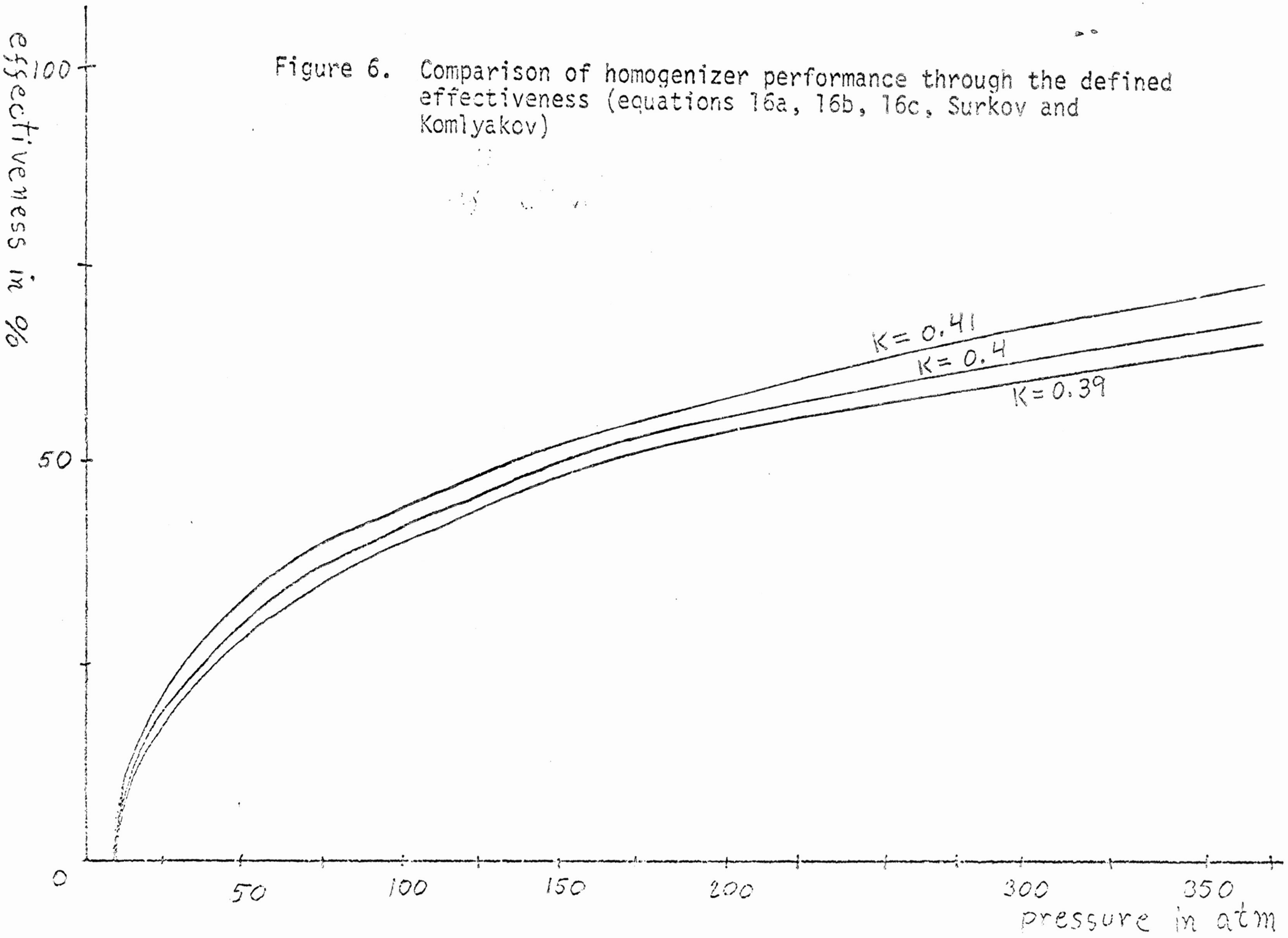


Figure 6. Comparison of homogenizer performance through the defined effectiveness (equations 16a, 16b, 16c, Surkov and Komlyakov)

Table 1. Comparison of homogenizer performance. (From Results II, solving together equations 14 and each of 15 to 18).

P	ef.	$214.6\sqrt[14]{P}-255$ from eq. 15	$\frac{227.4}{\sqrt[7]{10^{-0.39\log P}}}-255$ from eq. 16(a)	$\frac{227.4}{\sqrt[7]{10^{-0.4\log P}}}-255$ from eq. 16(b)	$\frac{227.4}{\sqrt[7]{10^{-0.41\log P}}}-255$ from eq. 16(c)	$190(P^{0.09786})-255$ from eq. 17(a)	$192(P^{0.09786})-255$ from eq. 17(b)	$171(P^{0.1143})-255$ from eq. 18
atm	psi							
25	368	15.11	17.11	18.37	19.63	5.3	8.1	-7.9
50	735	28.8	27.8	29.4	31	23.6	26.5	12.4
75	1103	37.2	34.3	36.1	37.9	34.89	38.	25.1
100	1470	43.2	39.	41.	42.85	43.2	46.3	34.5
150	2205	52.	45.7	47.84	50.	55.2	58.5	48.2
200	2200	58.4	50.5	52.86	55.2	64.1	67.5	58.3
300	4400	67.6	57.5	60.1	62.65	77.	80.5	73.2
400	5880	74.3	62.6	65.3	68.05	86.5	90.1	34.2
500	7350	79.6	66.5	69.41	72.3	94.	97.7	92.9

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