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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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BOGUSŁAW WEIGLE, ZYGMUNT SZPRENGIEL

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An Attempt to Assess the Erosion Damage Due to the Impact of a Polyfractional Rain of Droplets*

Several known methods of calculating the effects of erosion damage caused by monofractional and monokinetic stream of droplets have been described and compared to one another. A new equation describing the mean depth of damage in terms of the exposure time has been proposed for the case of such a stream of droplets. For the case of erosion damage caused by a polyfractional stream of droplets two known and two new methods of superimposing the erosion effects due to respective fractions of this stream have been presented and compared to one another. The authors consider the present paper to be a further step, after [1, 2, 3], towards the better prediction of the erosion damage progress.

Nomenclature

- a, b, c – constants in Eqs (23) and (24), dimensionless,
- b_1 – constant in Eq. (13), dimensionless,
- c_l, c_s – sound velocity in liquid and solid, resp. [ms^{-1}],
- d – droplet diameter [m],
- k – coefficient in Eq. (31),
- m – exponent,
- n – number of impacts per unit area [m^{-2}] or exponent,
- q – number of droplets per unit volume of rain [m^{-3}],
- p – exponent,
- P_S – impact pressure coefficient [$kg\,s^{-1}\,m^{-2}$],
- r – radial coordinate in surface plane [m],
- S – strength parameter, [Nm^{-2}],
- S_e, S_0 – normalized erosion resistance, dimensionless,
- U_a – total volume of water carried by droplets per unit area per unit time [$m^3\,m^{-2}\,s^{-1}$],
- U_e – value of the volume of material loss per unit area per unit time [$m^3\,m^{-2}\,s^{-1}$],
- U_{eM} – maximum instantaneous value of the volume of material loss per unit area per unit time [$m^3\,m^{-2}\,s^{-1}$],
- U_{eY} – average value of U_e for the time period τ resulting in a cumulative material loss of Y [$m^3\,m^{-2}\,s^{-1}$],
- w_N – normal component of the droplet impact velocity [ms^{-1}],
- Y – mean erosion depth [m],
- Y_0 – fictitious depth of erosion for $\tau=0$ (Fig. 1), [m],
- ν – Poisson's ratio, dimensionless,
- ρ_l, ρ_s – density of liquid and solid, resp., [kgm^{-3}],
- σ_u – ultimate tensile strength, [Nm^{-2}],
- τ – time period [s, h],

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Subscripts

H – Heymann,
i – discriminant of droplet fraction,
inc – incubation,
M – inflection point of the cumulative erosion – exposure time curve (Fig. 1),
res – resultant quantity,
S – Springer,
T – tangent point on the cumulative erosion-exposure time curve (Fig. 1),
YP – Yablonik, Poddubenko.

Introduction

The possibility of predicting the erosion damage on the surface of material due to the impact of droplets depends on the information on:

1) the amount of impacting droplets, their size, velocities and physical properties,

2) the effect of erosive action of the stream of droplets impacting on the material surface.

The present work deals with the second problem.

The erosion of materials in machinery parts such as turbine rotor blades and aircraft components is caused by droplets varying in size and possible velocities. A stream consisting of such droplets is called a polyfractional one.

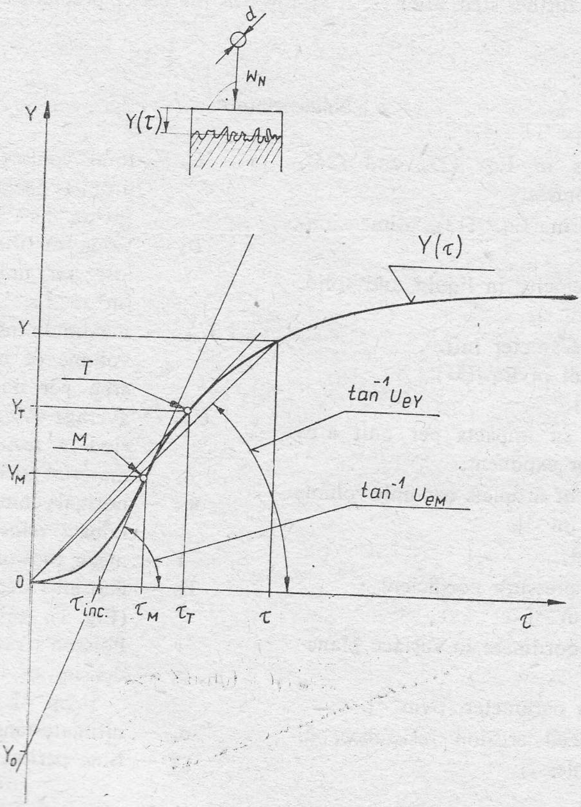

Fig. 1. Basic notation for the erosion depth vs exposure time relation

Up to now the determination of the effect of erosive action of a stream of droplets impinging on the surface of material has been based more or less on empirical formulae based on results of experiments with a monofractional and monokinetic stream of droplets. Such formulae have been described and compared to one another.

When attempting to predict the erosion damage for polyfractional droplet streams, which prevail in the engineering practice, we come upon one of the basic difficulties: how to evaluate jointly the effect of respective droplet fractions. Two known and two new methods of superimposing erosion effects due to the respective fractions of droplets have been presented. The methods have been based on the assumption that for each single fraction of droplets the relation $Y=f[\tau, U_{eM}$ (w_N, d, U_a, erosion resistance of material)] is known, Fig. 1. Experimental verification of the methods presented here still remains an open question.

Assessment of erosion damage due to monofractional droplet stream

Consider first the erosion damage – exposure time dependences as assessed by Heymann, Springer, and Yablonik and Poddubenko. All these dependences concern the behaviour of homogeneous materials subjected to impingements of a uniformly distributed rain of identical droplets.

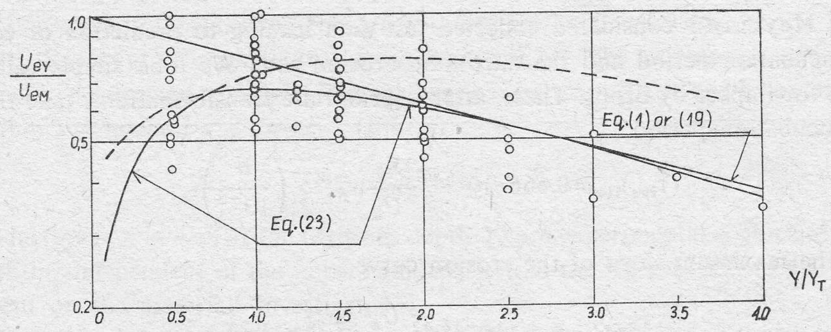

Fig. 2. U_{eY}/U_{eM} vs Y/Y_T approximation; experimental points after Heymann [4]

Results after Heymann: Heymann [4] has found that the least-squares fitting to data of the erosion – time history plotted in a normalized coordinate system U_{eY}/U_{eM}, Y/Y_T results in the following equation (Fig. 2),

$$U_{eY}/U_{eM}=\exp[-0.25Y/Y_T] \quad \text{for } Y/Y_T \geqslant 1, \tag{1}$$

where Y_T should be taken as an experimental constant [4], or a "typical" value equal to 250 μm [8], or according to equation after [4]

$$Y_T=1.4\cdot 10^{-2}\cdot d^{0.5}. \tag{2}$$

The definition of U_{eY} (Fig. 1) is

$$U_{eY}=\frac{Y}{\tau}. \tag{3}$$

For the maximum slope of the $Y(\tau)$ curve Heymann proposed the relation

$$(U_{eM})_{H1}=\frac{U_a}{S_e}\left(\frac{w_N}{2550}\right)^5. \tag{4}$$

Substituting Eq. (3) into Eq. (1) he obtained the erosion depth – exposure time relation:

$$\tau=Y(\dot{U}_{eM})_{H1}^{-1}\exp[0.25Y/Y_T]. \tag{5}$$

Further data collected by Heymann [3] present the following approximate influence of the droplet size on the maximum slope of the $Y(\tau)$ curve

$$(U_{eM})_{H2}=\frac{U_a}{S_e}\left(\frac{w_N}{2550}\right)^{4.92}\left(\frac{d}{10^{-3}}\right)^{(0.604+d^{-1}\cdot 1.14\cdot 10^{-4})}. \tag{6}$$

A similar relation for the maximum slope was used by Krzyżanowski and Szprengiel for prediction of the droplet size effect on the turbine blading erosion hazard [3]

$$(U_{eM})_{H3}=\frac{U_a}{S_e}\left(\frac{w_N}{2550}\right)^{4.92}\left(\frac{d}{10^{-3}}\right)^{1.69}. \tag{7}$$

In [5] Heymann considered collected test data leading to prediction of equations for the incubation period and the maximum erosion rate. We took simpler alternative equations for impact by drops. These, after appriopriate transformations, take the form: for the incubation period

$$(\tau_{inc})_{H4}=0.666\cdot 10^{16.06}\frac{S_0}{U_a}w_N^{-4.77}\left(\frac{d}{10^{-3}}\right), \tag{8}$$

and for the maximum slope of the erosion curve

$$(U_{eM})_{H4}=10^{-16.42}\frac{U_a}{S_e}w_N^{4.78}K_s^{-0.23}, \tag{9}$$

where K_s is the factor of shape of the target surface. For flat surfaces the factor K_s can be taken, after [5], as equal to 0.49.

In [5] Heymann did not deal with determination of an equation approximating the erosion depth – exposure time dependence.

Results after Springer [6]: Springer has taken into account only the erosion behaviour of materials within the exposure time not longer than $3\times\tau_{inc}$. He assumed that the experimental data can be approximated by two straight lines (Fig. 1)

$$Y=0 \quad \text{for } 0\leqslant\tau\leqslant\tau_{inc} \tag{10}$$

and

$$Y=(U_{eM})_S(\tau-\tau_{inc}) \quad \text{for } \tau_{inc}<\tau<3\,\tau_{inc}. \tag{11}$$

The maximum value of the increment of depth per time $(U_{eM})_S$ follows the equation

$$(U_{eM})_S = 140 U_a w_N^4 \left(\frac{P_S}{S}\right)^4_{\text{steel}} \frac{1}{S_e} \tag{12}$$

for

$$\left.\begin{aligned} P_S &= \frac{\rho_l c_l}{1+\dfrac{\rho_l c_l}{\rho_s c_s}}, \\ S &= \frac{4\sigma_u(b_1-1)}{1-2\nu}, \\ S_e &= \frac{(P_S/S)^4_{\text{steel}}}{(P_S/S)^4}. \end{aligned}\right\} \tag{13}$$

Fatigue considerations applied to material subjected to repeated liquid impingement result in the equation for the incubation period, τ_{inc},

$$(\tau_{inc})_S = 4.66 \cdot 10^{-6} \frac{d}{U_a w_N^{5.7}} \left(\frac{S}{P_S}\right)^{5.7}_{\text{steel}} S_0, \tag{14}$$

where

$$S_0 = \frac{(P_S/S)^{-5.7}}{(P_S/S)^{-5.7}_{\text{steel}}}.$$

The constants in Eqs (12) and (14) are obtained from the test data.

Results after Yablonik and Poddubenko [7]: The erosion damage behaviour of the material subjected to droplet impingement has been approximated by a single straight line within the interval $\tau_{inc} < \tau < \tau_M$, (Fig. 1)

$$Y = k_{YP} \rho_l U_a w_N^n \tau + Y_0. \tag{15}$$

The factors k, n as well as the fictitious depth Y_0 are experimental coefficients and were found to be independent of the impact velocity within the interval 200 to 400 ms^{-1} and dependent on the materials investigated.

Furthermore, it was found that the droplet diameter within the interval 400 to 1000 µm would not affect the erosion if the quantity of impacting water per unit area was the same.

Using previous nomenclature we introduce the maximum slope U_{eM} of the $Y(\tau)$ curve. Then we have

$$(U_{eM})_{YP} = k_{YP} \rho_l U_a w_N^n \tag{16}$$

and Eq. (15) can be rewritten in the form

$$Y = \tau (U_{eM})_{YP} + Y_0. \tag{17}$$

According to Fig. 1 for $\tau = \tau_{inc}$ there is $Y=0$, hence we get an expression for the incubation period

$$(\tau_{inc})_{YP} = -Y_0/(U_{eM})_{YP}. \tag{18}$$

Determination of the erosion depth – exposure time dependence

For experimental points of Y/Y_T and Y/Y_M above 1.0 Heymann [4] obtained, using the least-squares method, the following equation:

$$U_{eY}/U_{eM}=\exp[-0.25Y/Y_T], \tag{19}$$

and

$$U_{eY}/U_{eM}=1.026\exp[-0.236Y/Y_M]. \tag{20}$$

On the contrary, in [6, 7] the authors considered only the region $Y<Y_M$ in which they used a linear approximation for the dependence $Y(\tau)$, Fig. 1,

$$Y=U_{eM}(\tau-\tau_{\text{inc}}). \tag{21}$$

In this case, after taking $U_{eY}=Y/\tau$ and substituting τ from the Eq. (21), one obtains for the quotient U_{eY}/U_{eM}

$$U_{eY}/U_{eM}=(1-Y_0/Y)^{-1}, \tag{22}$$

where Y_0 is a fictitious depth of erosion for $\tau=0$ (the value of Y_0 is negative).

In order to find an expression which would approximate the erosion progress obtained xperimentally in both regions, i.e. for $Y\leqslant Y_M$ and $Y>Y_M$, we introduce the relation*)

$$U_{eY}/U_{eM}=a(Y/Y_T)^b\exp[c\cdot Y/Y_T]. \tag{23}$$

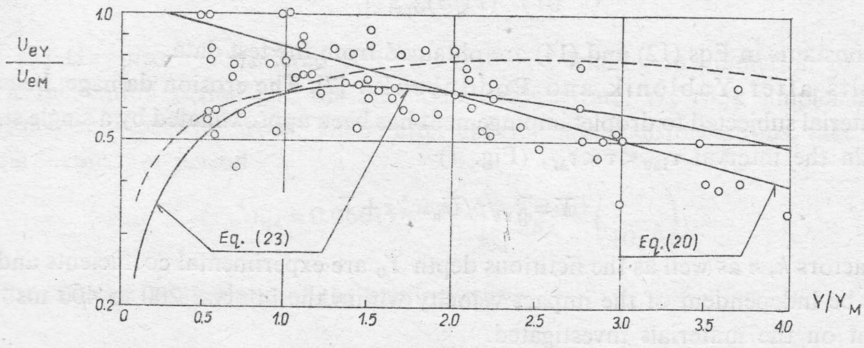

Fig. 3. U_{eY}/U_{eM} vs Y/Y_M approximation; experimental points after Heymann [4]

According to the definition of U_{eY} (cf. Eq. (3)), Eq. (23) can be rewritten as follows

$$\tau=Y\cdot U_{eM}^{-1}a^{-1}(Y/Y_T)^{-b}\exp[-cY/Y_T]. \tag{24}$$

Only the experimental results presented by Heymann [4, 8] in the form $U_{eY}/U_{eM}=$ $=f(Y/Y_T)$ and $U_{eY}/U_{eM}=f(Y/Y_M)$ which cover the values of erosion depth $Y\leqslant Y_T$ and $Y>Y_T$ have been taken into consideration (Figs 2 and 3).

To determine the values of the constants a, b, c in Eqs (23) and (24) the least-squares

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* It should be mentioned that equations (23) and (24) have been taken by the authors so as to approximate the available experimental data on erosion curves. It is also worth noting that large discrepancies existed between these data – cf. also Ref. [14] (*Editor's note*).

method was applied to all the points presented in Fig. 2. Besides, Eqs (23) and (24) should satisfy the following conditions:

1) the derivative of function (24) should be equal to infinity at $Y=0$

$$\partial\tau/\partial Y|_{Y=0}=\infty, \tag{25}$$

2) the derivative of function (24) should be equal to the inverse value of U_{eM} at $Y=Y_M$

$$\partial\tau/\partial Y|_{Y=Y_M}=1/U_{eM}, \tag{26}$$

3) the second derivative of function (24) should be equal to zero at $Y=Y_M$

$$\partial^2\tau/\partial Y^2|_{Y=Y_M}=0, \tag{27}$$

4) function (23) should reach a maximum at $Y=Y_T$ (Fig. 2)

$$\left.\frac{\partial(U_{eY}/U_{eM})}{\partial(Y/Y_T)}\right|_{Y/Y_T=1.0}=0. \tag{28}$$

The dependence of Y_T on Y_M can be found by equating relations (19) and (20). Hence we get the ratio $Y_T/Y_M=1.42$ which seems to be an average value of those listed in [4].

Unfortunately, functions (23) and (24) could not satisfy simultaneously the least--squares fit to points in Fig. 2 and the conditions as quoted above. For this reason we divide the region under consideration into two parts (see Figs 2 and 3): the first part for $Y\leqslant Y_M$ and the other one for $Y>Y_M$.

For function (24) in the first region, $Y\leqslant Y_M$, conditions 1 through 3 were applied together with the requirement of equality of functions (24) and (23) for both regions at $Y=Y_M$.

To determine function (23) for the second region the least-squares fit to all the points in Fig. 2 and condition 4 were applied. The authors realize that a division into the two regions has no physical argumentation.

Thus we obtained finally the values of constants a, b, c for the searched functions (23) or (24) as specified in Table 1. Both relations can be expressed as well in terms of Y_M instead of Y_T. Then the constants a, b, c take appropriate values as listed in Table 1..

Table 1

	Y/Y_M		Y/Y_T	
	$\leqslant 1.0$	>1.0	$\leqslant 1/1.42$	$>1/1.42$
a	0.8273406	0.8715714	1.0077892	1.0000000
b	0.5626526	0.3920000	0.5626526	0.3920000
c	−0.2239750	−0.2760563	−0.3180445	−0.3920000

It can be found easily that function (23) at the point $Y/Y_M=1.0$ takes the value $U_{eY}/U_{eM}=0.6613224$ which is close to 0.66666.. as given by Springer [6].

Such precise values of the constants a, b, c and other derived magnitudes result from the mathematical processing of experimental data and from conditions (25) to (28) applied to Eqs (23) and (24). Therefore, they should not be regarded as a very good fit to experimental curves $Y(\tau)$.

Comparison of the characteristic magnitudes of the erosion damage curve

Characteristic quantities of the curve $Y(\tau)$, as defined in Fig. 1, are the maximum slope U_{eM}, the incubation period τ_{inc} and the erosion depth Y_M at the point M where the slope of the curve begins to diminish. Only the relation for the maximum slope of the erosion curve has been determined by all the authors mentioned earlier. They have also given relations for one of the two remaining parameters (see Tables 4, 5 and 6). Table 2 contains experimental data which have been used for assessing the erosion relations for U_{eM}, τ_{inc} or Y_M.

Table 2

	Author				
	Heymann [4] 1969	Yablonik a. Poddubenko [7], 1974	Springer [6], 1976	Krzyża-nowski and Szprengiel [3], 1978	Heymann [5], 1979
d [mm]	0.1 to 1.2	0.4 to 1.0	0.64 to 2.0	0.1 to 2.2	1.2 to 2.0
w_N [ms^{-1}]	137 to 527	200 to 400	163 to 682	~100 to 400	140 to 400

In order to be able to compare all the relations to one another one should choose the material for which the erosion resistance can be specified in the form of constant coefficients S_0 and S_e. The necessary data and erosion resistance coefficients used in the methods under consideration are listed in Table 3. Since water is taken as the colliding liquid we have the density of water $\rho_l = 10^3$ kgm^{-3} and the velocity of sound in water $c_1 = 1463$ ms^{-1}.

The missing expressions for τ_{inc} or Y_M were determined based on relations resulting from the previous chapter, i.e. $Y_T/Y_M = 1.42$ and $U_{eY}/U_{eM} = 0.6613...$ at the point M (Fig. 1). Thus, we get the following expressions

$$\tau_M = 2.9526614\tau_{inc} \tag{29}$$

and

$$Y_M = 1.9526614\tau_{inc} \cdot U_{eM}. \tag{30}$$

Each parameter can be written in the following form:

$$U_{eM}, \quad \tau_{inc}, \quad Y_M = k \cdot U_a^m \cdot w_N^n \cdot (d \cdot 10^3)^p \cdot (\text{erosion resistance}). \tag{31}$$

Let us note that this equation is dimensionally inconsistent and therefore other physical quantities should also be involved.

For all the relations indicated previously the values of the coefficients k, m, n, p relating to the respective parameters are listed in Tables 4, 5 and 6. To show the differences among the expressions for U_{eM}, τ_{inc} and Y_M relative values of $U_{eM}/(U_{eM})_{YP}$, $\tau_{inc}/(\tau_{inc})_{YP}$, $Y_M/(Y_M)_{YP}$ plotted against the droplet size for the impact velocity $w_N = 300$ ms^{-1} are shown in Figs 4, 5 and 6. For all the parameters the values given by Yablonik and Poddubenko have been taken as the reference. Thick lines in Figs 4, 5 and 6 indicate the range

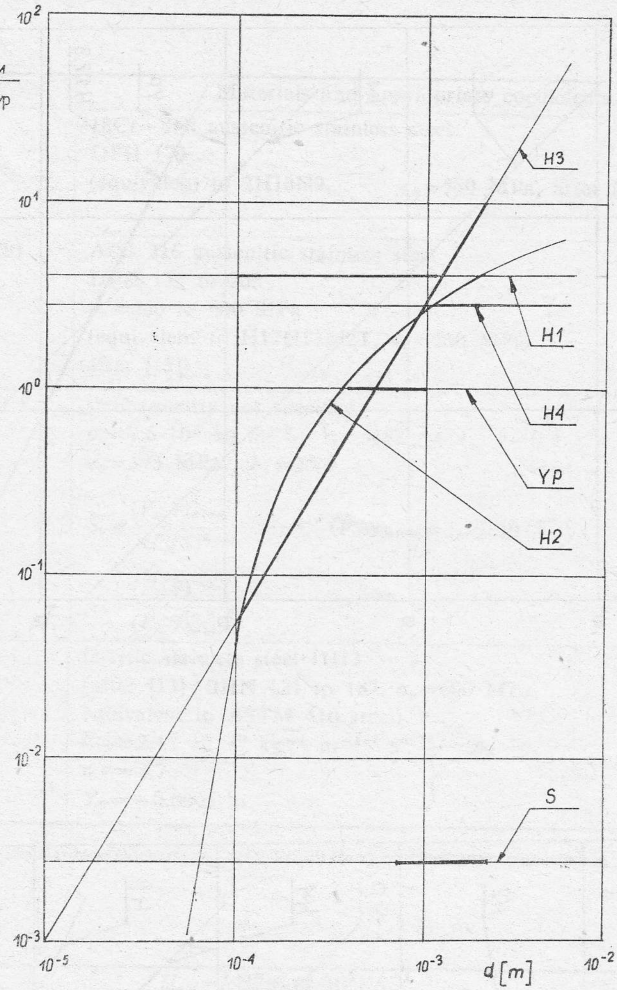

Fig. 4. Variation of relative values $U_{eM}/(U_{eM})_{YP}$ vs droplet size d

of droplet diameters used by the several authors to assess the erosion relations U_{eM}, τ_{inc} or Y_M. The results of comparison are valid only for steel of properties indicated in Table 3.

Examination of Figs 4, 5 and 6 shows that:

1) the best coincidence of the foregoing relations – except the one after Springer – takes place for droplet sizes in the range of about $0.7<d<2$ mm,

2) the quantities U_{eM}, τ_{inc} and Y_M have been determined by Yablonik and Poddubenko [7] without taking into account the droplet size,

3) the quantities U_{eM}, τ_{inc} and Y_M determined by Springer [6] differ much from those obtained by other methods: their values come closer to the ones after Heymann relations H2 and H3 [3] for droplet size d less than about 0.1 mm,

4) the quatities U_{eM} and τ_{inc} as given by Heymann relations H2 show heavy dependence upon droplet size, especially in the region of small droplets.

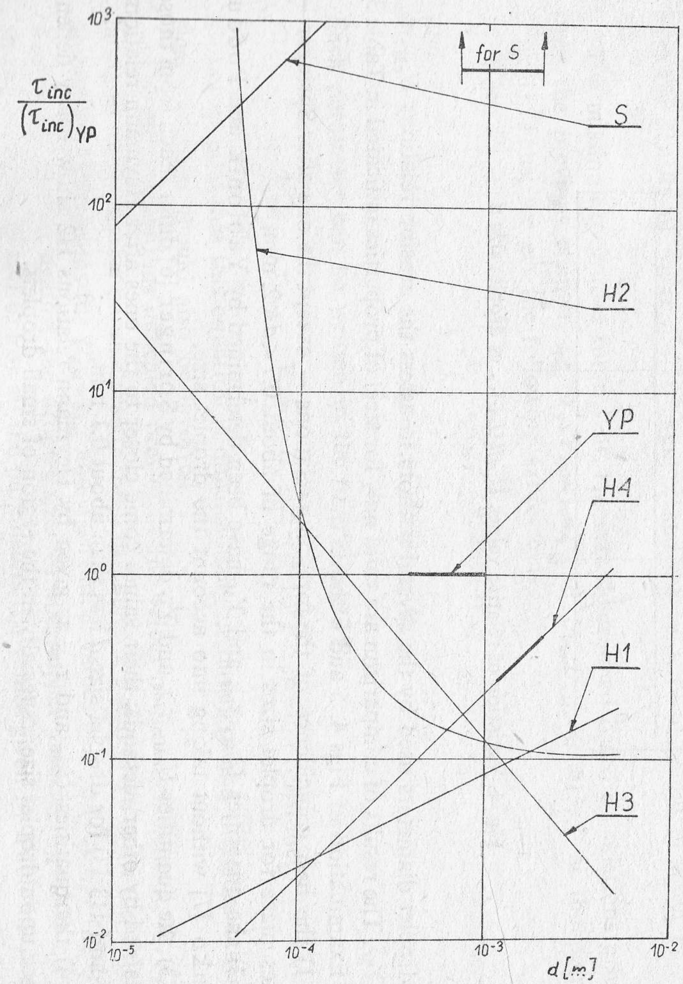

Fig. 5. Variation of relative values $\tau_{inc}/(\tau_{inc})_{YP}$ vs droplet size d

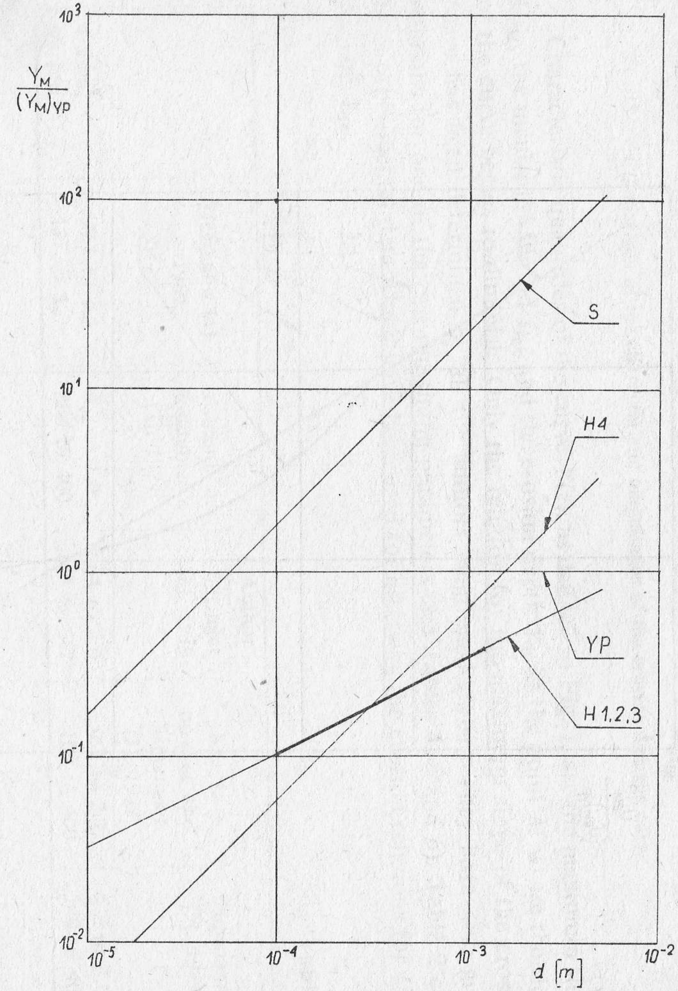

Fig. 6. Variation of relative values $Y_M/(Y_M)_{YP}$ vs droplet size d

Table 3

Relation	Materials and appriopriate coefficients
Heymann 1 (4) Heymann 2 (6) Heymann 3 (7)	18Cr−8Ni austenitic stainless steel DPH 170 (equivalent to 2H18N9, $\sigma_u=580$ MPa, after [13]) $S_0=S_e=1$
Heymann 4 (8), (9)	AISI 316 austenitic stainless steel DPH 153 to 205 $\sigma_u=550$ to 600 MPa (equivalent to H17N13M2T, $\sigma_u=550$ MPa, after [13]) $S_0=S_e=1$
Springer (12), (14)	steel (quality not specified) $\rho_s=7.6\cdot10^3$ kg m^{-3}, $c_s=5182$ ms^{-1}, $\nu=0.3$ $\sigma_u=593$ MPa, $b_1=20.9$ $S_e=\frac{(P_s/S)^4_{\mathrm{steel}}}{(P_s/S)^4}$ $(P_s/S)_{\mathrm{steel}}=1.19\cdot10^{-5}$ $S_0=\frac{(P_s/S)^{-5.7}}{(P_s/S)^{-5.7}_{\mathrm{steel}}}$; $S_0=S_e=1$
Yablonik, Poddubenko (16), (17)	ferritic stainless steel 1H13 (after [13]: BHN 121 to 187, $\sigma_u=600$ MPa, equivalent to ASTM 410 steel) $k_{\mathrm{YP}}=2.17\cdot10^{-20}$ kg^{-1} m$^{-1.7}$ s$^{4.7}$ $n=4.7$ $Y_0=-0.0005$ m $S_0=S_e=1$

The DPH-Diamond Pyramide Hardness (Vickers) and BHN-Brinell Hardness Number are equivalent in the range up to about 300

Table 4

Relation		$U_{eM}=kU_a^m w_N^n (d\cdot10^3)^p S_e^{-1}$			
		k	m	n	p
Heymann 1	(4)	$1.55\cdot10^{-17}$	1	5.00	0
Heymann 2	(6)	$1.55\cdot10^{-17}$	1	4.92	$0.604+\frac{1.14\cdot10^{-4}}{d}$
Heymann 3	(7)	$1.55\cdot10^{-17}$	1	4.92	1.69
Heymann 4	(9)	$4.48\cdot10^{-17}$	1	4.78	0
Springer	(12)	$2.86\cdot10^{-18}$	1	4.00	0
Yablonik, Poddubenko	(16)	$2.17\cdot10^{-17}$	1	4.70	0

Heymann [5] stated on the basis of a large amount of experimental results that the value of the product $R_e\cdot N_0$ is close to unity, where $R_e=U_{eM}/U_a$ and N_0 the number of specific impacts corresponding to $H_0=U_a\tau_{\mathrm{inc}}$. For drops $N_0=1.5\ H_0d^{-1}$, after [5]. Then one gets $R_e\cdot N_0=1.5U_{eM}\tau_{\mathrm{inc}}d^{-1}\cong1$ or $U_{eM}\tau_{\mathrm{inc}}\cong0.66\cdot10^{-3}\ (d\cdot10^3)$. Then, as a next step of comparison we shall check the products $U_{eM}\cdot\tau_{\mathrm{inc}}$ using respective relations given in Tables 4 and 5. The results are listed in Table 7 together with a numerical example for

Table 5

Relation		$\tau_{inc}=kU_a^m w_N^n (d\cdot 10^3)^p S_0$			
		k	m	n	p
Heymann 1	—	$1.028\cdot 10^{13}$	-1	-5.00	0.5
Heymann 2	—	$1.028\cdot 10^{13}$	-1	-4.92	$-(0.104+\frac{1.14\cdot 10^{-4}}{d})$
Heymann 3	—	$1.028\cdot 10^{13}$	-1	-4.92	-1.19
Heymann 4	(8)	$0.762\cdot 10^{13}$	-1	-4.77	1
Springer	(14)	$5.334\cdot 10^{19}$	-1	-5.70	1
Yablonik, Poddubenko	(18)	$2.304\cdot 10^{13}$	-1	-4.70	0

Table 6

Relation		$Y_M=k\cdot U_a^m w_N^n (d\cdot 10^3)^p S_0 S_e^{-1}$			
		k	m	n	p
Heymann 1	(2)	$3.111\cdot 10^{-4}$	0	0	0.5
Heymann 2	(2)	$3.111\cdot 10^{-4}$	0	0	0.5
Heymann 3	(2)	$3.111\cdot 10^{-4}$	0	0	0.5
Heymann 4	—	$6.666\cdot 10^{-4}$	0	0.01	1
Springer	—	$2.971\cdot 10^{2}$	0	-1.7	1
Yablonik, Poddubenko	—	$9.763\cdot 10^{-4}$	0	0	0

Table 7

Relation	Formula $U_{eM}\cdot\tau_{inc}$, values for $d=1$ mm, $w_N=300$ m/s	
Heymann 1	$0.1593\cdot 10^{-3}\cdot(d\cdot 10^3)^{0.5}$	$0.1593\cdot 10^{-3}$
Heymann 2	$0.1593\cdot 10^{-3}\cdot(d\cdot 10^3)^{0.5}$	$0.1593\cdot 10^{-3}$
Heymann 3	$0.1593\cdot 10^{-3}\cdot(d\cdot 10^3)^{0.5}$	$0.1593\cdot 10^{-3}$
Heymann 4	$0.341\cdot 10^{-3}\cdot(d\cdot 10^3)\cdot w_N^{0.01}$	$0.361\cdot 10^{-3}$
Springer	$152.5\cdot(d\cdot 10^3)\cdot w_N^{-1.7}$	$9.38\cdot 10^{-3}$
Yablonik, Poddubenko	$0.5\cdot 10^{-3}$	$0.5\cdot 10^{-3}$

$d=1$ mm and $w_N=300$ ms^{-1}, as mean values acceptable for all experimental data shown in Table 2. All values of the product $U_{eM}\tau_{inc}$, except the one after Springer, come close to $0.66\cdot 10^{-3}$ within a range of an order of magnitude. The value due to Springer's relations exceeds this limit.

According to Fig. 1 the product $U_{eM}\tau_{inc}$ defines the fictitious depth $Y_0=-U_{eM}\tau_{inc}$.

Assessment of erosion damage due to polyfractional droplet stream

To the best knowledge of the present authors the erosion damage effects due to simultaneous impingement of droplets of different diameters and velocities have never been investigated experimentally in a manner adequate to experiments with monofractional droplet streams as quoted, among others, by Heymann [4, 5] or Springer [6].

Therefore, the methods of assessment of erosion damage due to a polyfractional stream of droplets have to be based on theoretical considerations only.

Up to now two methods of superposition of the erosion effects due to polyfractional droplet stream impingement have been used.

The first method has been based on the conception of simple addition of the depth Y of erosion caused by each droplet fraction as acting independently in the same time period τ (Fig. 7) i.e.

$$Y_{\text{res}} = \sum_i Y(\tau)_i . \tag{32}$$

This method has been used by Valha [9] in connection with Heymann's approximation of the erosion effects due to a monofractional droplet stream, Eq. (5).

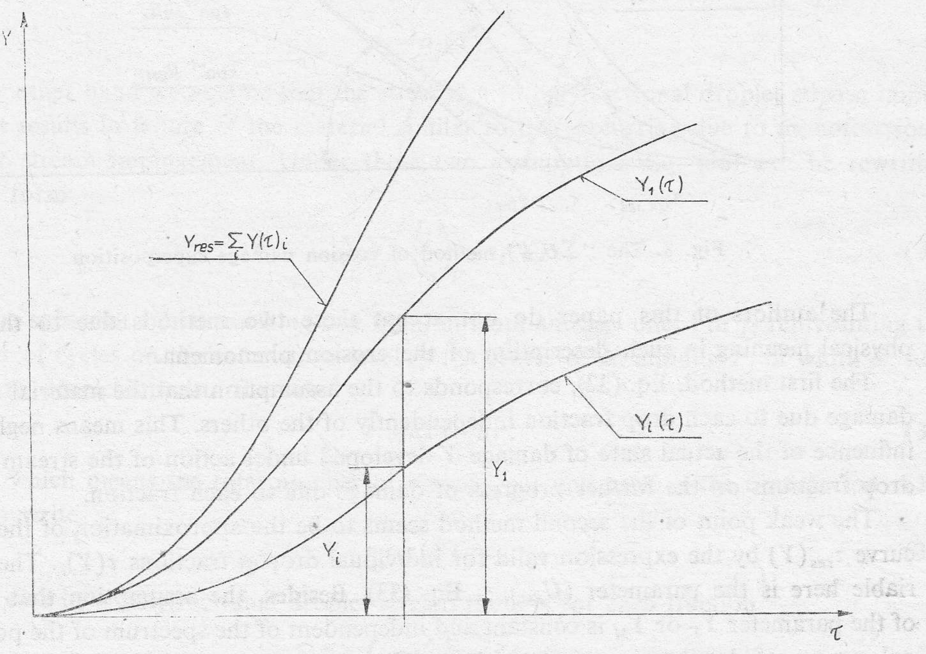

Fig. 7. The "ΣY" method of erosion damage superposition

The second method is based on the assumption that the value of U_{eM} for a polyfractional droplet stream is equal to the simple sum of values of U_{eMi} for respective fractions i composing the stream of droplets (Fig. 8) i.e.

$$(U_{eM})_{\text{res}} = \sum_i U_{eMi} . \tag{33}$$

This method was used by Krzyżanowski [1], Krzyżanowski and Weigle [2], Krzyżanowski and Szprengiel [3] and by Valha [10]. All of them used the Heymann's approximation for the total damage quantity in the form

$$\tau = Y(U_{eM})_{\text{res}} \exp[0.25 Y/Y_T], \tag{34}$$

where Y_T was taken to be constant and equal to 200 μm [2, 3] or 250 μm [8, 10].

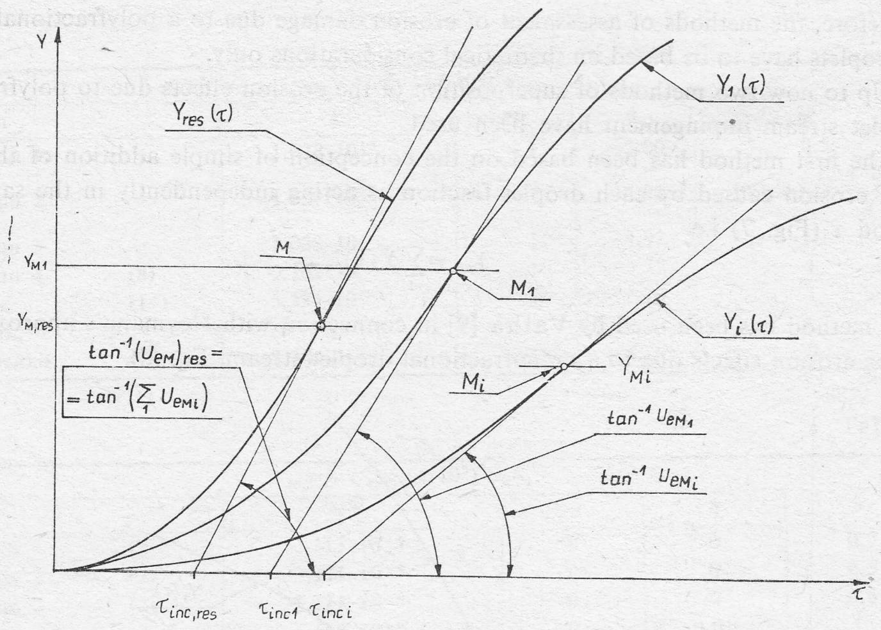

Fig. 8. The "ΣU_{eM}" method of erosion damage superposition

The authors of this paper do not accept these two methods due to the lack of physical meaning in such description of the erosion phenomena.

The first method, Eq. (32), corresponds to the assumption that the material undergoes damage due to each drop fraction independently of the others. This means neglecting the influence of the actual state of damage Y developed under action of the stream of all the drop fractions on the further progress of damage due to each fraction.

The weak point of the second method seems to be the approximation of the resultant curve $\tau_{res}(Y)$ by the expression valid for individual droplet fractions $\tau(Y)_i$. The only variable here is the parameter $(U_{eM})_{res}$, Eq. (33). Besides, the assumption that the value of the parameter Y_T or Y_M is constant and independent of the spectrum of the polyfractional stream of droplets is questionable.

Poddubenko and Yablonik [11] have come to the same conclusion under assumption that superposition of the erosion damage caused by each fraction of droplets follows the rule of superposition for a fatigue load [7]. They have applied this method together with the linear approximation of the test data as mentioned in the previous section. This resulted into

$$Y_{res}(\tau) = \tau(U_{eM})_{res} + Y_0 \tag{35}$$

with $(U_{eM})_{res}$ as given by Eq. (33).

Two other methods of assessment of the total erosive effects due to impingement of a polyfractional droplet stream will be presented below.

Conception I: summing of the time periods $\Sigma\, 1/\tau$.

This method is very close to the one applied by Springer [6] who assumed that the failure mechanism of eroded materials subjected to repeated liquid impacts is similar to the failure mechanism of bars subjected to repeated torsion and bending. For a monofractional stream of droplets Springer applied the Miner's rule expressed by the equation

$$\sum_j \frac{f_j}{N_j} = a_1 , \tag{36}$$

where $f_1, f_2, \ldots, f_j \ldots$ represent the number of cycles in which the material is subjected to specified overstress levels $\sigma_1, \sigma_2, \ldots, \sigma_j \ldots$; $N_1, N_2, \ldots, N_j \ldots$ represent the life, in cycles, at these overstress levels. The factor a_1 is an experimental constant. It can be assumed that the factor a_1 does represent an inner state of the eroded material (the state of the structure of the material, its strain and/or energy level, etc.). We presume that the depth Y of the material removed represents that inner state of the material. Then the factor a_1 should be a function of the depth Y, i.e.

$$a_1 = a_1(Y) .$$

On the other hand we assume that the stress due to polyfractional droplet stream impingement results in failure of the material similar to that occurring due to monofractional droplet stream impingement. Under these two assumptions Eq. (36) can be rewritten in the form

$$\sum_i \sum_j \left(\frac{f_j}{N_j}\right)_i = a_1(Y) \tag{37}$$

with the subscript i distinguishing one fraction from another one. For f_j representing the number of cycles on the same stress level in the centre of an annulus r_j of width dr subjected to droplet impacts there is

$$f_j = n 2\pi r_j \, dr . \tag{38}$$

For n, which means the total number of impacts per unit area in the time period $\tau(Y)$, we can write

$$n = \tau(Y) \, q w_N . \tag{39}$$

In the case of a polyfractional droplet stream there is for each fraction

$$f_{ji} = n_i 2\pi r_j \, dr \tag{40}$$

and

$$n_i = \tau(Y)_i \, q_i \, w_{Ni} . \tag{41}$$

The radial distance r_j varies continuously from zero to infinity. Thus Eq. (37), substituting Eq. (40), may be rewritten

$$\sum_i \int_0^\infty \frac{n_i 2\pi r \, dr}{N_i} = a_1(Y) . \tag{42}$$

To integrate this equation we have followed the solution of Springer and obtained

$$\sum_i \left[n_i \frac{\pi}{4} d_i^2 \left(\frac{P_i}{S}\right)^{a_2(Y)} \right] = a_1(Y) . \tag{43}$$

Substituting Eq. (41) into Eq. (43) yields

$$\tau(Y)\cdot\sum_i\left[q_i w_{Ni}\frac{\pi}{4}d_i^2\left(\frac{P_i}{S}\right)^{a_2(Y)}\right]=a_1(Y). \tag{44}$$

According to Springer, for a single droplet fraction acting up to the depth Y there is

$$\tau(Y)_i q_i w_{Ni}\frac{\pi}{4}d_i^2\left(\frac{P_i}{S}\right)^{a_2(Y)}=a_1(Y). \tag{45}$$

The factors $a_1(Y)$ and $a_2(Y)$ are still functions of the depth only. Replacing in Eq. (44) the expression in brackets by $a_1(Y)/\tau(Y)_i$ from Eq. (45) we get

$$\tau(Y)\cdot\sum_i\frac{a_1(Y)}{\tau(Y)_i}=a_1(Y). \tag{46}$$

Finally, the equation for the time period τ_{res} needed to cause damage of the depth Y due to polyfractional droplet stream impingement takes the form (Fig. 9)

$$\tau_{res}=\left(\sum(\tau(Y))_i^{-1}\right)^{-1}. \tag{47}$$

Conception II: summing of the instantaneous depth increments $\Sigma\, \Delta Y$.

The second conception introduced by the authors is based on the assumption that for any given state of erosion damage as expressed by Y, the further increase of depth dY is a sum of instantaneous values of increments of depth dY_i, at this depth Y, due to each of fractions of the polyfractional droplet stream, i.e.

$$dY=\sum_i(dY)_i. \tag{48}$$

Moreover, we assumed that the instantaneous increments of depth dY_i do not depend

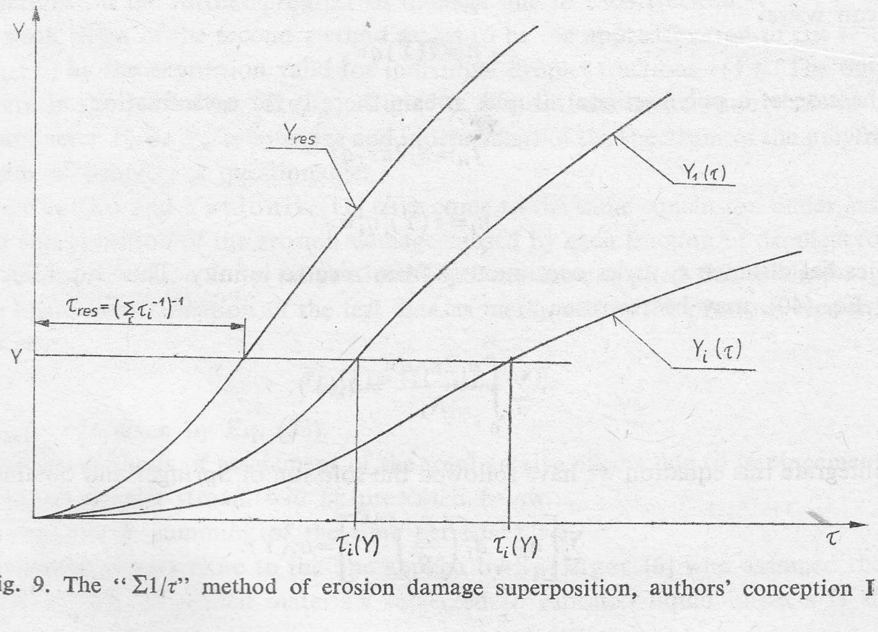

Fig. 9. The "$\Sigma 1/\tau$" method of erosion damage superposition, authors' conception I

on the previous progress of damage (until the depth Y is reached); we came to this conclusion after examining the test results of [11] and [12]. Hence, the instantaneous increments dY_i depend on the derivatives $(\partial Y/\partial \tau)_i$ determined relative to the depth Y and for each of the droplet fraction acting individually, i.e.

$$(dY)_i = \left(\frac{\partial Y}{\partial \tau}\right)_i d\tau. \tag{49}$$

Substituting Eq. (49) into (48) and integrating over the time period needed to reach the

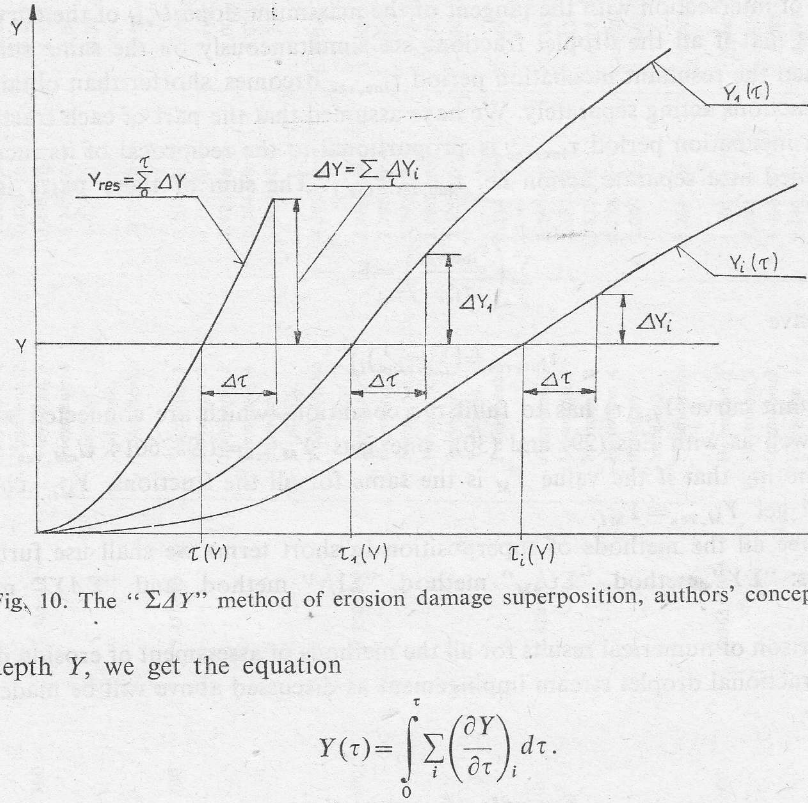

Fig. 10. The "$\Sigma\Delta Y$" method of erosion damage superposition, authors' conception II

total depth Y, we get the equation

$$Y(\tau) = \int_0^{\tau} \sum_i \left(\frac{\partial Y}{\partial \tau}\right)_i d\tau. \tag{50}$$

For numerical calculations the integral should be replaced by a sum, which requires a suitable choice of the time-step $d\tau$. Then Eqs (48) to (50) may be rewritten as (see Fig. 10):

$$\Delta Y = \sum_i (\Delta Y)_i, \tag{51}$$

$$(\Delta Y)_i = \left(\frac{\partial Y}{\partial \tau}\right)_i \Delta\tau, \tag{52}$$

and

$$Y_{res} = \sum_0^{\tau} \sum_i \left(\frac{\partial Y}{\partial \tau}\right)_i \Delta\tau. \tag{53}$$

To obtain for each droplet fraction the values of time periods $\tau(Y)_i$ appearing in Eq. (47)

or the derivatives $(\partial Y/\partial\tau)_i = 1/(\partial\tau/\partial Y)_i$ needed for Eq. (53) one can use one of the equations $\tau(Y)$ from the preceding paragraph.

In the method of ΣU_{eM} superposition the resultant curve $Y(\tau)$ is given by equation (24), where the value of $U_{eM,\,\mathrm{res}}$ should be taken instead of that of U_{eMi}. Furthermore, the value of Y_M should be determined as the one appropriate to all the fractions. Up to now, e.g. in [2, 3, 8, 10], experimental values of Y_M have been taken into consideration. Let us consider the effect of simultaneous action of the polyfractional droplet stream fractions. The effect of each fraction acting separately results in a curve $Y_i(\tau)$ as shown in Fig. 8. As it is well known, the incubation period τ_{inc} is defined as the value of the abscissa at the point of intersection with the tangent of the maximum slope U_{eM} of the curve $Y(\tau)$. It is obvious that if all the droplet fractions act simultaneously on the same surface of the target then the resultant incubation period $\tau_{\mathrm{inc,\,res}}$ becomes shorter than obtained for any of the fractions acting separately. We have assumed that the part of each fraction i in the resultant incubation period $\tau_{\mathrm{inc,\,res}}$ is proportional to the reciprocal of its incubation period obtained in a separate action i.e. $\tau_{\mathrm{inc,\,res}}/\tau_{\mathrm{inc},\,i}$. The sum of these parts is equal to unity

$$\sum_i \left(\frac{\tau_{\mathrm{inc,\,res}}}{\tau_{\mathrm{inc}}}\right)_i = 1\,.$$

Hence we have

$$\tau_{\mathrm{inc,\,res}} = \left(\sum(\tau_{\mathrm{inc}}^{-1})_i\right)^{-1}.$$

As the resultant curve $Y_{\mathrm{res}}(\tau)$ has to fulfil the conditions which are connected with the Eq. (24) as well as with Eqs (29) and (30), one gets $Y_{M,\,\mathrm{res}} = 1.9526614\, U_{eM,\,\mathrm{res}} \cdot \tau_{\mathrm{inc,\,res}}$. It is worth noting that if the value Y_M is the same for all the fractions, $Y_{Mi} = \text{constant}$, then we will get $Y_{M,\,\mathrm{res}} = Y_{Mi}$.

To describe all the methods of superposition in short terms we shall use further on abbreviations: "ΣY" method, "ΣU_{eM}" method, "$\Sigma 1/\tau$" method, and "$\Sigma \Delta Y$" method, respectively.

A comparison of numerical results for all the methods of assessment of erosion damage due to polyfractional droplet stream impingement as discussed above will be made in the next chapter.

Example of computation

To illustrate the above-presented considerations an example of computation of the erosion damage due to a polyfractional stream of droplets is given.

The conceptions of superposition of erosion effects due to a polyfractional stream of droplets have been based on the assumption that erosion effects due to a monofractional and monokinetic droplet stream are known.

Expression (24) has been used to assess the erosion depth vs exposure time curve due to each fraction separately.

Numerical calculations have been performed for a stream consisting of five fractions with droplet diameters $d = 0{,}6$; 0.8; 1.0; 1.2; 1.4 mm and one droplet impact velocity equal to $w_N = 300\ \mathrm{ms}^{-1}$. The total volumetric intensity of impacting water derived from the

Table 8

Fraction	d [m]	w_N [m s^{-1}]	U_a [m s^{-1}]	Relation	U_{eM} [m h^{-1}]	τ_{inc} [h]	Y_M [m]
1	$0.6\cdot10^{-3}$	300	$0.965\cdot10^{-4}$	Heymann 1	$1.308\cdot10^{-5}$	$9.444\cdot10^{0}$	$2.413\cdot10^{-4}$
				Heymann 2	$5.526\cdot10^{-6}$	$2.233\cdot10^{1}$	$2.413\cdot10^{-4}$
				Heymann 3	$3.496\cdot10^{-6}$	$3.522\cdot10^{1}$	$2.413\cdot10^{-4}$
				Heymann 4	$9.146\cdot10^{-6}$	$2.011\cdot10^{1}$	$3.591\cdot10^{-4}$
				Springer	$8.045\cdot10^{-9}$	$6.995\cdot10^{5}$	$1.098\cdot10^{-2}$
				Yablonik, Poddubenko	$3.309\cdot10^{-6}$	$1.510\cdot10^{2}$	$9.763\cdot10^{-4}$
2	$0.8\cdot10^{-3}$	300	$2.410\cdot10^{-4}$	Heymann 1	$3.267\cdot10^{-5}$	$4.366\cdot10^{0}$	$2.786\cdot10^{-4}$
				Heymann 2	$1.752\cdot10^{-5}$	$8.130\cdot10^{0}$	$2.786\cdot10^{-4}$
				Heymann 3	$1.420\cdot10^{-5}$	$1.001\cdot10^{1}$	$2.786\cdot10^{-4}$
				Heymann 4	$2.284\cdot10^{-5}$	$1.073\cdot10^{1}$	$4.788\cdot10^{-4}$
				Springer	$2.009\cdot10^{-8}$	$3.734\cdot10^{5}$	$1.465\cdot10^{-2}$
				Yablonik, Poddubenko	$8.265\cdot10^{-6}$	$6.049\cdot10^{1}$	$9.763\cdot10^{-4}$
3	$1.0\cdot10^{-3}$	300	$3.250\cdot10^{-4}$	Heymann 1	$4.406\cdot10^{-5}$	$3.620\cdot10^{0}$	$3.115\cdot10^{-4}$
				Heymann 2	$2.792\cdot10^{-5}$	$5.706\cdot10^{0}$	$3.115\cdot10^{-4}$
				Heymann 3	$2.792\cdot10^{-5}$	$5.694\cdot10^{0}$	$3.115\cdot10^{-4}$
				Heymann 4	$3.080\cdot10^{-5}$	$9.951\cdot10^{0}$	$5.986\cdot10^{-4}$
				Springer	$2.709\cdot10^{-8}$	$3.461\cdot10^{5}$	$1.831\cdot10^{-2}$
				Yablonik, Poddubenko	$1.114\cdot10^{-5}$	$4.486\cdot10^{1}$	$9.763\cdot10^{-4}$
4	$1.2\cdot10^{-3}$	300	$2.410\cdot10^{-4}$	Heymann 1	$3.267\cdot10^{-5}$	$5.348\cdot10^{0}$	$3.412\cdot10^{-4}$
				Heymann 2	$2.352\cdot10^{-5}$	$7.421\cdot10^{0}$	$3.412\cdot10^{-4}$
				Heymann 3	$2.817\cdot10^{-5}$	$6.181\cdot10^{0}$	$3.412\cdot10^{-4}$
				Heymann 4	$2.284\cdot10^{-5}$	$1.610\cdot10^{1}$	$7.183\cdot10^{-4}$
				Springer	$2.009\cdot10^{-8}$	$5.602\cdot10^{5}$	$2.197\cdot10^{-2}$
				Yablonik, Poddubenko	$8.265\cdot10^{-6}$	$6.049\cdot10^{1}$	$9.763\cdot10^{-4}$
5	$1.4\cdot10^{-3}$	300	$0.965\cdot10^{-4}$	Heymann 1	$1.308\cdot10^{-5}$	$1.442\cdot10^{1}$	$3.686\cdot10^{-4}$
				Heymann 2	$1.044\cdot10^{-5}$	$1.805\cdot10^{1}$	$3.686\cdot10^{-4}$
				Heymann 3	$1.464\cdot10^{-5}$	$1.285\cdot10^{1}$	$3.686\cdot10^{-4}$
				Heymann 4	$9.146\cdot10^{-6}$	$4.692\cdot10^{1}$	$8.380\cdot10^{-4}$
				Springer	$8.045\cdot10^{-9}$	$1.632\cdot10^{6}$	$2.564\cdot10^{-2}$
				Yablonik, Poddubenko	$3.309\cdot10^{-6}$	$1.510\cdot10^{2}$	$9.763\cdot10^{-4}$

five fractions amounts to

$$U_a = \sum_i U_{ai} = 10^{-3} \mathrm{m^3 m^{-2} s^{-1}}.$$

The chosen droplet diameters and impact velocity fall approximately into the range used in the experimental investigations (Table 3).

The values of characteristic erosion parameters of the individual fractions of droplets computed using the respective methods of assessment of erosion of a monofractional stream of droplets are collected in Table 8.

It has been assumed in computation of the erosion damage that the impact velocity w_N is independent of the droplet size. Furthermore, a Gaussian distribution of mass concentration of the colliding water has been assumed for the five fractions of droplets (Table 8). The normalized erosion resistance of the material under consideration is taken to be equal to unity as for chromium-nickel steel, $S_e = 1$.

Figures 11, 12 and 13 show the results of superposition of erosion damage for several methods of superposition, i.e. "ΣY", "ΣU_{eM}" and "$\Sigma 1/\tau$" respectively, and for various relations of erosion parameters for the monofractional stream of droplets.

Computations for the method of superposition "ΣU_{eM}" have been conducted twice. Once for the constant value $Y_{M,\,\mathrm{res}} = (Y_{Mi})_{\max}$ for which the results are shown in Fig. 12, and the second time for $Y_{M,\,\mathrm{res}} = 1.9526614\, U_{eM,\,\mathrm{res}} \cdot \tau_{\mathrm{inc,\,res}}$ (Eq. (30)). For the latter

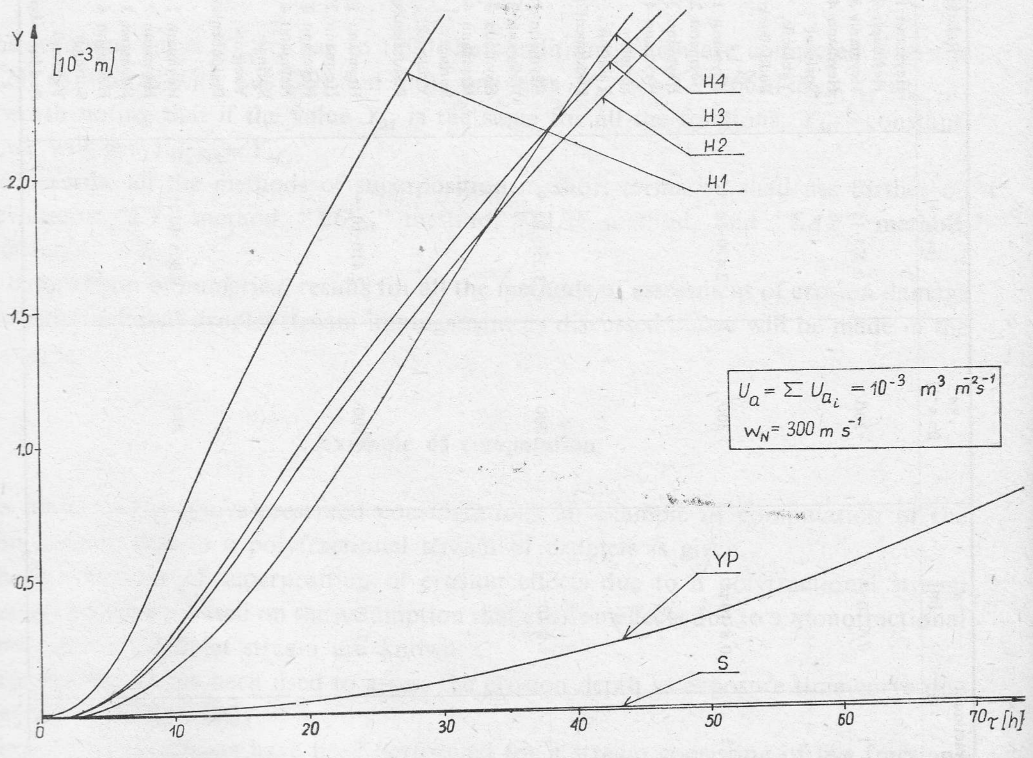

Fig. 11. Variation of the erosion depth Y vs exposure time τ due to polyfractional stream of droplets; the "ΣY" method of erosion damage superposition

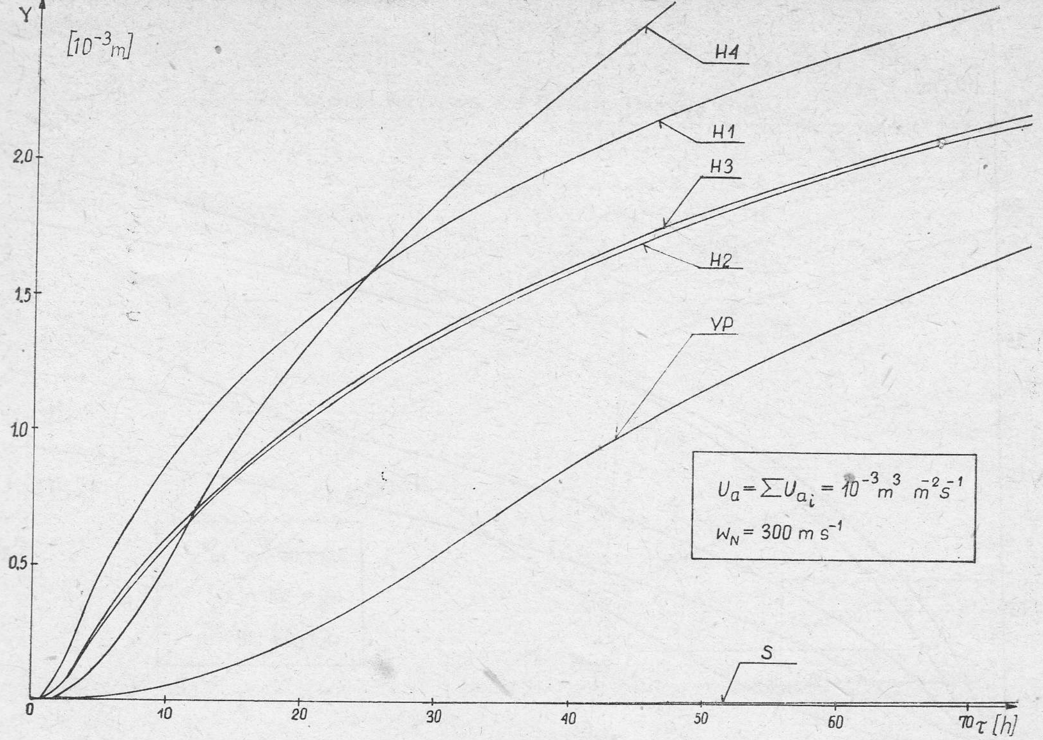

Fig. 12. Variation of the erosion depth Y vs exposure time τ due to polyfractional stream of droplets; the "ΣU_{eM}" method of erosion damage superposition

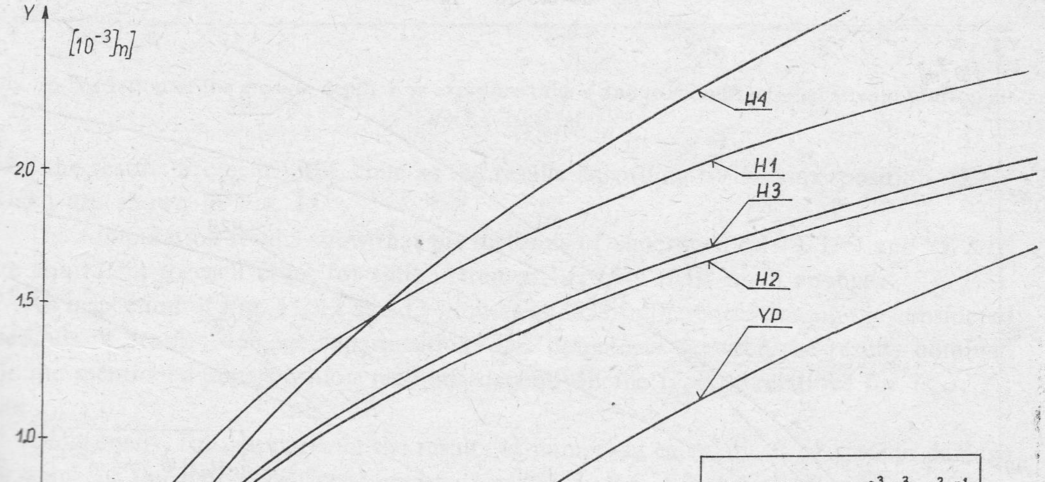

Fig. 13. Variation of the erosion depth Y vs exposure time τ due to polyfractional stream of droplets. the "$\Sigma 1/\tau$" method of erosion damage superposition

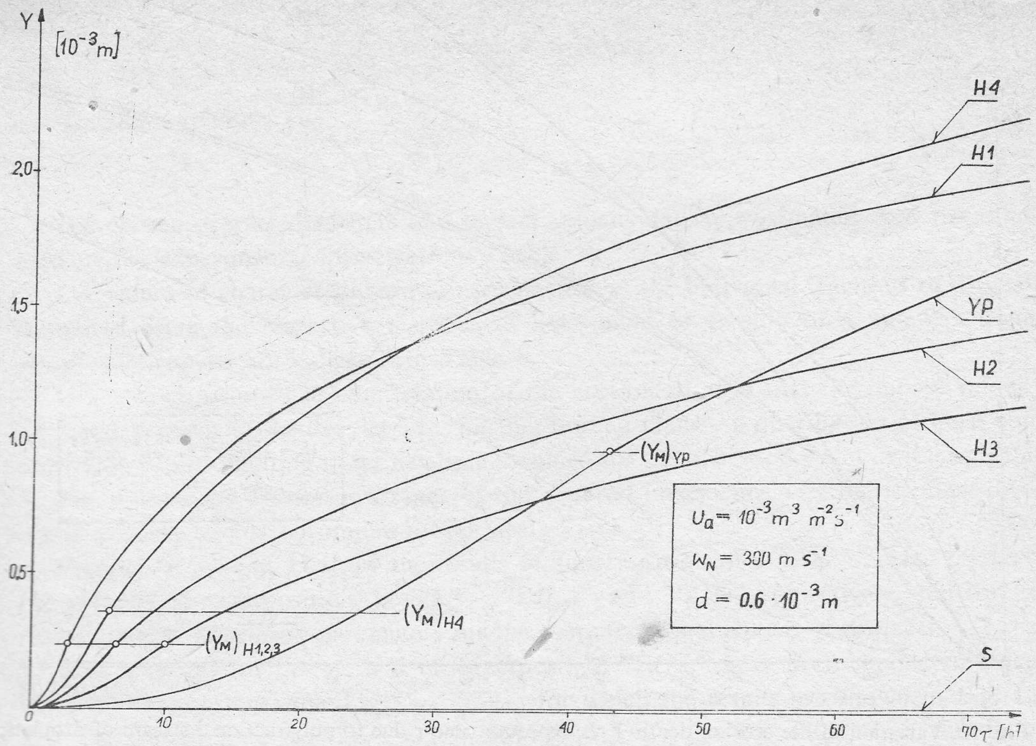

Fig. 14. Variation of the erosion depth Y vs exposure time τ due to monofractional stream of droplets, $d=0.6 \cdot 10^{-3}$ m

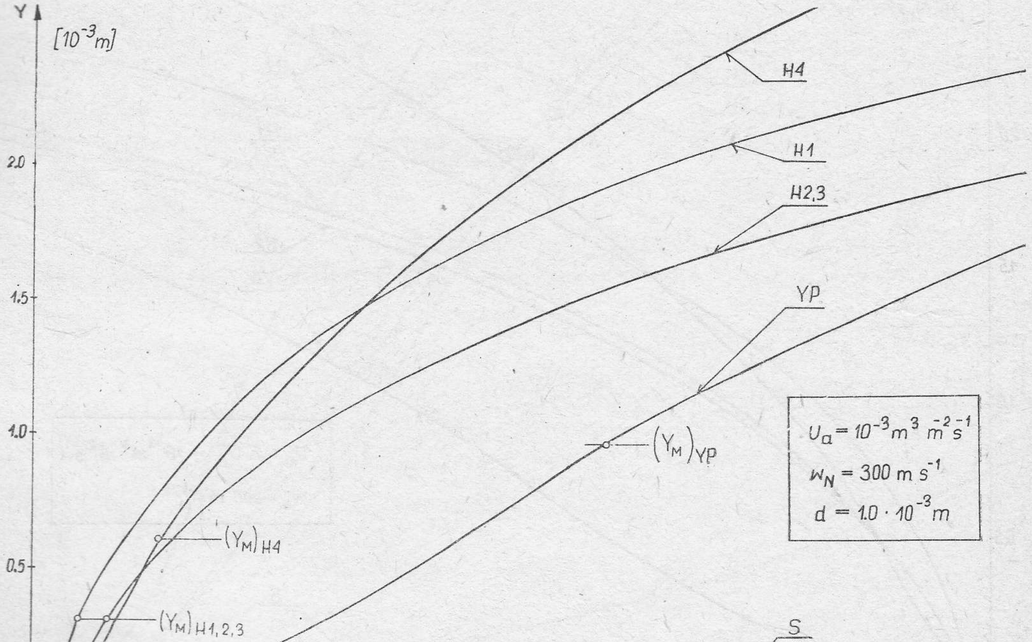

Fig. 15. Variation of the erosion depth Y vs exposure time τ due to monofractional stream of droplets, $d=1.0 \cdot 10^{-3}$ m

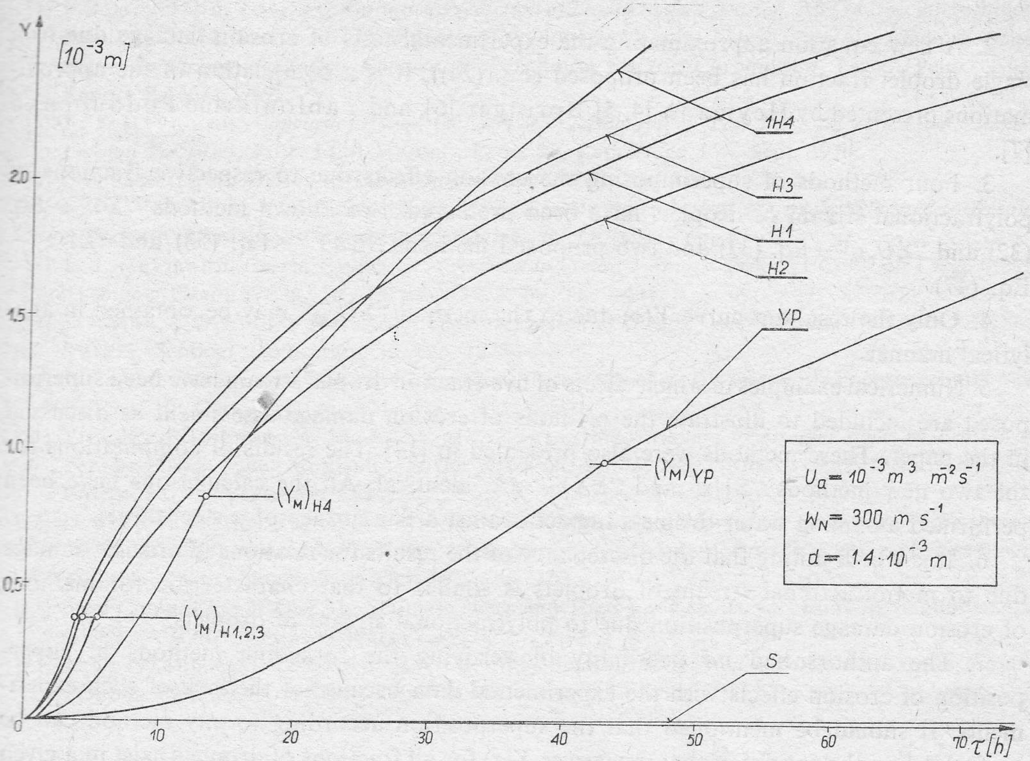

Fig. 16. Variation of the erosion depth Y vs exposure time τ due to monofractional stream of droplets $d=1.4\cdot10^{-3}$ m

case the results are nearly the same as the results according to the superposition "$\Sigma 1/\tau$" which are shown in Fig. 13.

The computation results show that the methods of superposition "$\Sigma\, 1/\tau$" and "$\Sigma\, \Delta Y$" are equivalent to each other for time increment $\Delta\tau$ (Eq. (53)) small enough.

An inspection of Figs 11, 12 and 13 shows significant differences among the considered methods of erosion damage superposition. The differences between the results obtained for the mentioned superposition methods depend on the type of relations for U_{eM}, Y_M and τ_{inc}.

Additionally, for comparison, the results of numerical calculations of erosion damage for some of the individual fractions of droplets, $d=0.6$; 1.0; 1.4 mm, and for various methods of assessment of erosion parameters have been presented in Figs 14, 15 and 16. The quantity of colliding water carried by each fraction of droplets is the same and equal to $U_a=10^{-3}$ $m^3m^{-2}s^{-1}$.

Conclusions

1. Several relations, after Heymann, Springer, and Yablonik and Poddubenko describing the characteristic erosion parameters U_{eM}, τ_{inc}, Y_M due to monofractional stream of droplets have been presented and compared to one another. The convergence of these relations depends mainly on the droplet size.

2. A new equation approximating the experimental tests of erosion damage due to a single droplet fraction has been proposed (Eq. (24)). It is a compilation of the approximations presented by Heymann [4, 5], Springer [6], and Yablonik and Poddubenko [7].

3. Four methods of superimposing the erosion effects due to respective fractions of polyfractional stream of droplets have been presented: two known methods "ΣY" – Eq. (32) and "ΣU_{eM}" – Eq. (33) and two proposed methods "$\Sigma \Delta Y$" – Eq. (53) and "$\Sigma 1/\tau$" – Eq. (47).

4. Only the resultant curve $Y(\tau)$ due to the method "ΣU_{eM}" may be obtained in analytical manner.

5. Numerical examples in which effects of five-fraction droplet stream have been superimposed are included to illustrate the methods of erosion damage assessment as discussed in the paper. These methods were also presented in [14]. The results of computations for the two new methods "$\Sigma 1/\tau$" and "$\Sigma \Delta Y$" are identical. All the calculations have been performed assuming water droplets impact against a flat surface of a steel target.

6. It is worth noting that the discrepancy of the results for relations of erosion damage due to monofractional stream of droplets is similar to that characteristic for methods of erosion damage superposition due to polyfractional stream of droplets.

7. The authors had no possibility of verifying the foregoing methods of superposition of erosion effects with the experimental data because of the lack of such experiments. It should be mentioned that the superposition according to any method can be performed on the condition that the curves $Y(\tau)$ for all fractions of droplets exist in a given range of time τ.

8. A program of experimental investigations aimed at verifying the erosion curves both for monofractional and polyfractional droplet streams has been worked out.

9. In the case of superposition of fractions that need a very wide range of exposure time an analytical representation for the curve beyond the resultant time limit τ_{res} is needed. Therefore, in our opinion it is insufficient to give a linear approximation up to the exposure time τ_M of the results for each individual monofractional droplet stream as proposed by Heymann [5], Springer [6], Yablonik and Poddubenko [7]. The approximating exponential relation after Heymann [4] valid only for the values $Y > Y_T$ is also an insufficient representation.

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Próba oceny zniszczeń erozyjnych wywołanych uderzeniami wielofrakcyjnego deszczu kropel

Streszczenie

Wyniki badań erozyjnego niszczenia materiału poddanego uderzeniom kropel przedstawiane są najczęściej w postaci wykreślnej zależności ubytków materiału od czasu oddziaływania jednofrakcyjnego strumienia lub deszczu kropel. W urządzeniach technicznych, w których występują zjawiska erozji (łopatki wirnikowe turbin parowych, elementy samolotów poddanych działaniu deszczu atmosferycznego itd.), z reguły występują krople o szerokim zakresie wymiarów i prędkości, przy równocześnie niejednorodnym rozmieszczeniu w przestrzeni. Stojąc przed zadaniem wyznaczenia (postawienia prognozy) postępu zniszczeń erozyjnych w warunkach pracy urządzenia technicznego natrafiamy na jedną z podstawowych trudności: sposób łącznego ujęcia wpływu poszczególnych frakcji kropel.

W pracy zebrano w pierwszej kolejności znane zależności wiążące czas oddziaływania kropel, ich parametry charakterystyczne oraz wielkość powstałych ubytków materiału wskutek kolizji z monofrakcyjnym deszczem kropel.

Następnie przedstawiono dwie dotychczas stosowane oraz dwie proponowane przez autorów metody wyznaczania zniszczeń sumarycznych w funkcji czasu oddziaływania wielofrakcyjnego deszczu kropel. Pierwsza z proponowanych metod oparta jest na założeniu o zmęczeniowym charakterze zjawiska powstawania i postępu zniszczeń. Druga zaś, na założeniu, że w kolejnych, dostatecznie krótkich przedziałach czasu oddziaływania, każda z frakcji kropel wywołuje taki przyrost zniszczeń, jaki by powstał przy jej samodzielnym oddziaływaniu. Dotychczas brak materiału eksperymentalnego pozwalającego zweryfikować jakąkolwiek z przedstawionych metod. Autorzy przygotowują program badań eksperymentalnych zmierzających do ich weryfikacji.

Попытка оценки эрозионных повреждений вызванных ударами многофракционного дождя капель

Резюме

Результаты эрозионных исследований повреждения материала подвергающегося ударам капель представляются чаще всего в виде графика зависимости убылей материала от времени воздействия однофракционного потока или дождя капель. В технических устройствах, в которых возникают эрозионные явления (рабочие лопатки паровых турбин, элементы самолетов подвергающиеся действию атмосферического дождя и т.д.), как правило выступают капли в широком диапазоне размеров и скоростей при одновременно неоднородном распределении в пространстве. Решая задачу определения (поставления прогноза) развития эрозионных повреждений в условиях работы технического устройства встречают одно из основных затруднений: способ совместного представления влияния отдельных фракций капель.

В работе собраны в первую очередь известные зависимости связывающие время воздействия капель, их характерные параметры, а также величину возникших убылей материала вследствие колизии с монофракционным дождем капель.

Затем представлены два до сих пор применяемые и два предлагаемые авторами метода определения суммарных повреждений в функции времени воздействия многофракционного дождя капель. Первый из предлагаемых методов основан на предположении усталостного характера явления возникновения и развития повреждений. Второй метод основан на предположении, что в очередных, достаточно коротких пределах времени воздействия, каждая из фракций капель вызывает такой прирост повреждений, какой возникал бы при ее самостоятельном воздействии. До сих пор не хватает экспериментального материала позволяющего проверить любой из представленных методов. Авторами подготовляется программа экспериментальных исследований направленных на их проверку.