Vector Analysis of Ionic Collision on CaCO₃ Precipitation Based on Vibration Time History

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Abstract. Vibration effects on the piping system can result from the internal factor of fluid or the external factor of the mechanical equipment operation. As the pipe vibrated, the precipitation process of CaCO₃ on the inner pipe could be affected. In the previous research, the effect of vibration on CaCO₃ precipitation in piping system was clearly verified. This increased the deposition rate and decreased the induction time. However, the mechanism of vibration control in CaCO₃ precipitation process as the presence of vibration has not been recognized yet. In the present research, the mechanism of vibration affecting the CaCO₃ precipitation was investigated through vector analysis of ionic collision. The ionic vector force was calculated based on the amount of the activation energy and the vibration force was calculated based on the vibration sensor data. The vector resultant of ionic collision based on the vibration time history was analyzed to prove that vibration brings ionic collision randomly to the planar horizontal direction and its collision model was suspected as the cause of the increasing deposition rate.

Keywords: CaCO₃; vector; ionic collision; vibration

1. Introduction

Mechanical vibration is often encountered in the piping system industries when the pipe transports some fluid from a point to other points during the industrial processes. The vibration can be caused by internal and external factors. The internal factor is usually generated by the flowing fluid [1-5] which is often called as fluid-induced vibration [1,5-6]. Moreover, the external factor can be caused by the operation of mechanical equipment such as an electric pump, blower, extruder, compressor [7] diesel engine, and a turbine which is called as external excitation [6-7].

In a certain condition, the internal and external factors can vibrate the piping system simultaneously and produce some forces, which have been investigated previously by Morison [8-9]. In the Morison equation, the relationships among the inertia force, drag force, and excitation force obviously described [7,10] the strength of the piping system structure to function without a rupture [7,10]. This Morison equation can still be applied by researchers for the time being [9] but other researchers have a
different direction in particular crystallization and scaling process fields. As the fluid in the pipes is vibrated by internal and external forces, and affected by physical and chemical factors, it brings the curiosity to discover their influences in the precipitation process.

The influences of vibration on CaCO$_3$ scale formation in piping system include increasing the deposition rate, decreasing the induction time, and controlling the crystal polymorph and crystal phases [11]. To justify the origin of such phenomena, many factors are suspected as the mechanism of the vibration in affecting the precipitation. First, vibration force can promote the ionic collision through increasing ionic force when the ions collide with others. Second, the vibration might change the ionic displacement as vibration direction.

The collision of CaCO$_3$ ions during the precipitation process of the vibrating system may occur in a different manner since the hydrodynamic force affects the system [11]. Drag force, inertia force as part of the flowing force and excitation force as a function of vibration force [9-11] take in as the primary part of the precipitation process. The system will be different in the strength of the ionic force and the direction of the ionic displacement. An appropriate method to investigate this phenomenon is using vector analysis of ionic collision based on Vibration Time History (VTH). Furthermore, the present research was undertaken to understand the mechanism of deposition rate in CaCO$_3$ precipitation due to the presence of mechanical vibration.

2. Experimental Method

2.1 Experimental design
The concept of the experimental design was here described firstly as guidance in the performance of the research. The calculated deposition rate was used to derive the activation energy (Ea) as suggested by Arrhenius [12] according to the Equation (1) below.

$$k = A \exp\left[-\frac{Ea}{RT}\right]$$

Where $k$ is deposition rate (M.s$^{-1}$); $A$ is the frequency of effective collision; exp is an exponential number; $Ea$ is activation energy (kJ/mol); $R$ is ideal gas constant, and $T$ is the temperature in K. Furthermore, the activation energy found was used to derive ionic force by dividing the amount by the number of one mol CaCO$_3$ ion, and by the time needed to produce one mol CaCO$_3$. The vibration force inserted to the system as also calculated in the N/ion unit based on the sensor data of the experiment. The ionic shape was defined as spherical or nearly spherical as it had been investigated by Marcus [13] even for (Ca$^2+$) or (CO$_3^{2-}$) ion. Usually, the ionic collision may occur between monoatomic ions, diatomic ions, triatomic ions and polyatomic ions [14]. The collision also can occur between ion-atom, atom-atom or atom-molecule [15]. Even in this research, collision was investigated between ion-ion since the material had been diluted in the solvent. The ionic collision was defined as a perfect bouncing collision in which the energy of the collision was bounced totally [12]. Four arrangement of ionic vector direction was chosen as the representation of randomness displacement i.e. by the angle of 900; 600; 300 and 00 to the horizontal axis. The resultant between ionic and vibration forces was calculated step by step in accordance with the vibration direction as it had been recorded through Vibration Time History until the ion direction is the same as the vibration direction.

2.2 Material
CaCO$_3$ precipitation was carried out experimentally by mixing CaCl$_2$ and Na$_2$CO$_3$ solutions which were supplied by Merck$^5$ according to the reaction in equation (2).

$$\text{CaCl}_2 (aq) + \text{Na}_2\text{CO}_3 (aq) \rightarrow \text{CaCO}_3 (s) + 2\text{NaCl} (aq)$$

The concentration of calcium in the solution was determined to be 3.500 ppm, prepared by dissolving 77.175 gr of CaCl$_2$ into 6,000 mL of demineralized water. Sodium solution was also prepared by
dissolving 55.65 gr of Na₂CO₃ into the 6,000 mL demineralized water. The solution was subsequently filtrated two times by 0.22 μm micropore® paper to ensure that the unwanted particles remained in the solution. Each of the solution was then stored in a covered vessel to avoid dust and other dirty materials. The chosen vessel was made from the material that was considered not to react with the solution and it must be strong enough when the solution was heated to 318 K.

2.3 Experimental rig

A built in-house experimental rig equipped with a computerized program control was employed to conduct the experiment as shown schematically in Figure 1. The rig consisted of two vessels (1) and (2) in which contained CaCl₂ and Na₂CO₃ solution respectively. A stirrer was attached in each vessel under a computer program control and automatically set at 30 rpm to ensure the homogeneous solution. All solution in each vessel was pumped by CHEM FEED Ca-92683 dosing pump (5) at a flow rate of 30 mL/min, and both solutions met in the test pipe section (6). The temperature was set by an electrical heater (3), which was immersed in the solution and controlled by a sensor (4) to keep it stable. When the various temperatures were set, a computer program sent a command to the pump to delay the operation for a couple of minutes until the right temperature condition was achieved.

In the test pipe section, four pairs of coupons were inserted in which a scale investigation was needed to form. The pipe was attached to the table (7) and vibrated mechanically by an electrical motor (8) which was set by a computer program (11). The vibration was operated at the frequency of 0.00; 4.00 and 8.00 Hz. Lutron VT-8204 Vibration Meter (9) was selected to record the vibration parameter such as peak to peak displacement (m), velocity (m/sec-RMS) and acceleration (m/sec²-RMS), and the results were shown by the computer program.

The solution conductivity was measured by a TDS meter supplied by Komatsu (10) after leaving the coupon, and the data were recorded by a computer program (11). A filter paper of 0.22 μm (12) was used to screen the crystals brought by the flowing solution. A flask tube (13) and a vacuum pump
(14) were employed to help the capture of those crystals. Finally, the solution was sent to the waste vessel (15).

2.4 Deposition rate

CaCO₃ deposition rate in the flows and vibration system was described in the previous research [11] as the modification of the formula given by Sheikholeslami [16] as follows:

\[ W_{\text{net}} = W_{\text{precipitation}} + W_{\text{strainer}} \]  (3)

Where \( W_{\text{net}} \) is net deposition rate (gr/hr), \( W_{\text{precipitation}} \) is deposition rate measured in coupon (g/hr) and \( W_{\text{strainer}} \) is deposition rate measured in the strainer (g/hr). The deposition rate was measured in three various temperatures, i.e. 298, 308 and 318 K, and also three vibration frequency of 0.00, 4.00 and 8.00 Hz. The crystals found in the coupon and in the strainer were dried in an electrical heater at 60 °C for six hours. The weighing was done using Ohaus AR-2140 analytical balance when the crystals were still attached in the coupon or strainer. Crystals were kept in a dry cup after being removed from the coupon and strainer. The crystal mass of the precipitation was found by calculating the difference between the coupon mass with crystals and the coupon mass without crystal. Meanwhile, the crystal mass of the strainer was found by calculating the difference between strainer mass with crystals and the strainer mass without crystal.

3. Results and Discussion

3.1. Deposition

After running for 4 hours, the deposition rate was determined by the equation (3) for non-vibrated and vibrated system. The results of scale deposition rate calculation are given in Table 1. It shows that the increase of the vibration frequency and temperature developed the CaCO₃ deposition rate. The influence of temperature on the deposition rate had been investigated by previous researchers [17-21] and is in the close agreement with this research in term of deposition rate at the frequency of 0.00 Hz. These deposition rates were subsequently used to calculate the activation energy.

| Frequency (Hz) | 298 K (gr/hr) | 308 K (gr/hr) | 318 K (gr/hr) |
|---------------|---------------|---------------|---------------|
| 0.00          | 5.2157        | 6.3471        | 7.8786        |
| 4.00          | 6.1614        | 7.1799        | 8.3942        |
| 8.00          | 8.5598        | 9.4510        | 10.5422       |

3.2. Vector force fields

The vector component in this system could be identified in three forces, i.e. ionic force, vibration force and flowing force. Drag and inertia forces determined the flowing force to be 0.00209 x 10⁻²³ N. These two forces were difficult to be drawn in a vector graph since their values were approximately 1/10,000 from other vectors. If drag and inertia forces were drawn in a vector system, their magnitude was atomic and therefore it would be better if these vectors were neglected.

The ionic collision force was calculated based on the activation energy of the reaction. On the other hand, the vibration force was calculated as the data were found by the sensor. The amount of the kinetic energy in order to be able to react should be at least similar to the amount of the activation energy (Ea). Referring to Arrhenius equation, the amount of the activation energy depends on the alteration of the solution temperatures [12]. Equation (4) expressed a linear model of Arrhenius equation in serving the calculation to be more simple and appropriate to the data found [12].
\[ \ln k = -(Ea/R)(1/T) + \ln A \quad \text{(4)} \]

where \( k \) is the reaction rate (M.sec\(^{-1}\)), \( A \) is the frequency of effective collision, \( R \) is ideal gas constant = 8,134 K, \( Ea \) is activation energy (kJ/mol), and \( T \) is temperature (K). Furthermore, the data listed in Table 2 were used in the calculation of the activation energy (\( Ea \)).

**Table 2. Calculation of \( \ln k - 1/T \)**

| \( \ln k \) (1/M.s\(^{-1}\)) | \( 1/T \) (K\(^{-1}\)) |
|-----------------------------|---------------------|
| -11.1432                   | 3.3355 x 10\(^{-3}\) |
| -10.9469                   | 3.2467 x 10\(^{-3}\) |
| -10.7308                   | 3.1446 x 10\(^{-3}\) |

The experiment was conducted in three various temperatures, i.e. 298, 308 and 318 K for all vibration frequency. As the reaction of such equation (2) was assumed not to be in reversible term since the order of reaction was defined as one. The deposition rate was calculated via such equation (3) and then converted to M.s\(^{-1}\) unit. To meet the equation (4), the deposition rate was converted to \( \ln k \) and the temperature was also converted to 1/T as listed in Table 2. Through Excel program, the values of 1/T and \( \ln k \) were plotted to determine the regression equation to find the gradient (\( m \)). The regression line of the Excel showed the equation of y line of which determinant \( R^2 \) value was one. The line showed that there is not a residue found in the y equation. The equation was:

\[ y = -2.170.4 x - 3.9156 \]

As the equation of linear regression of \( y = mx + n \), the value of \( m \) was -2,170.4 and \( n \) was -3.9156.

\[ Ea = -\frac{m \times R}{R} = -(2.170.4 \text{ J/mol}) \times (8.314 \text{ K}) \]

\[ Ea = 18,044 \text{ J/mol or 18.044 kJ/mol} \]

The value of \( Ea = 18.044 \text{ kJ/mol} \) was in good agreement with the work of Petrou [22]. Furthermore, the frequency of molecular collision was calculated as equation (5).

\[ A = k/e^{-Ea/RT} \quad \text{(5)} \]

Take the experiment of 318 K, of which reaction rate (k) was 21.8611 x 10\(^{-6}\) mol/sec, \( Ea = 18.044 \text{ kJ/mol, } R = 8.314 \text{ K} \), so the frequency of the collision (A) was found:

\[ A = 21.8611 \times 10^{-6} \times e^{-18.044/(8.314 \times 318)} = 21.8612 \times 10^{-6} \text{ mol collision} \]

As ion is an atom or a group of atoms that has a net positive or negative charge [12], so each CaCO\(_3\) molecule has two ions i.e. Ca ion in positive charge and CO\(_3\) ion in negative charge. Ionic effective collision (A) could be calculated as follow:

\[ A = 21.8612 \times 10^{-6} \text{ mol collision} \times (6.022 \times 10^{23} \text{ molecule/mol} \times 2 \text{ ion/molecule} \]

\[ A = 263.2963 \times 10^{17} \text{ ionic collision} \]

As the effective collision occurs between the two ions in positive and negative charge, the number of ions was as much as two times of the number of the collision [12] = 2 x 263.2963 x 10\(^{17}\) = 526.5926 x 10\(^{17}\) ions. To calculate the ionic force of the collision, take the experiment of 298 K, consider that ionic collision as a vector in trajectory \( Tr = 0.004 \text{ m} \) as vibration displacement. Ionic collision force named as \( F_{coll} \) and calculated using equation (6).
\[ F_{\text{coll}} = \frac{E_a \times 1.000 \text{ N/kJ}}{(N_A \times \text{reactant ion} \times t \times T_r)} \]  
\[ F_{\text{coll}} = \frac{18.044 \text{ kJ/mol} \times 1.000 \text{ N/kJ}}{(6.022 \times 10^{23} \text{ molecule} \times 2 \text{ ion} \times 45.693 \text{ sec} \times 0.004 \text{ m})} \]  
\[ F_{\text{coll}} = 8.2 \times 10^{-23} \text{ N/ion} \]

Where number 2 represents the amount of ions per molecule i.e. (Ca\(^{2+}\)) and (CO\(_3^{2-}\)) ions, Notation t stands as the time needed to produce one mol of CaCO\(_3\) which is calculated as a molar weight of CaCO\(_3\) divided by the weight of product resulted from the reaction per hour by the experiment. The calculation of the time needed was \( t = \frac{100 \text{ g}}{7.8786 \text{ g/hr}} = 12.6926 \text{ hr or 45.693 sec.} \)

In the current experiment of 8 Hz, the vibration sensor showed an acceleration of 22 m/sec\(^2\) RMS. The solution mass in the pipe with a flow rate of 30 mL/min was 0.0005 kg in every second, so then the force given to the system by vibration (\( F_{\text{vib}} \)) in ionic term was calculated as Equation (7).

\[ F_{\text{vib}} = \frac{m \times a}{\Sigma \text{ ion}} \]  
\[ F_{\text{vib}} = \frac{0.0005 \text{ kg} \times 22 \text{ m/sec}^2}{(526.5926 \times 10^{17} \text{ ion})} \]  
\[ F_{\text{vib}} = 21 \times 10^{-23} \text{ N/ion} \]

3.3. Vector analysis based on Vibration Time History (VTH)

Take four arrays of ionic vectors with displacement direction i.e. ion at 90° (a), 60° (b), 30° (c), and 0° (d) to the horizontal axis, as represented in random directions as shown in Figure 2. It had been calculated that the ionic force was \( 8.2 \times 10^{-23} \text{ N/ion} \). When vibration affected the system, a new vector of \( F_{\text{vib}} = 21 \times 10^{-23} \text{ N/ion} \) acted as the direction of vibration displacement to the ion.

![Figure 2](image)

**Figure 2.** Four arrays of ion direction representing random collisions. R is a resultant force, \( \alpha \) is the angle of collision direction to horizontal axis

Ionic vector interaction was analyzed through the means of Vibration Time History to reveal the vector alteration sequentially from the initial to the final conditions in which the angle of ion position was close to 0° to the horizontal axis. In Vibration Time History of 8 Hz, every displacement occurred in 0.06 sec, so ionic collision was analyzed at every 0.06 seconds. The collision was defined as a perfectly elastic collision in which the energy of the collision was totally bounced. From the calculation, the initial ionic force had been found to be \( 8.2 \times 10^{-23} \text{ N} \) and the vibration force was \( 21 \times 10^{-23} \text{ N} \).

Furthermore, the Ionic and vibration vector was analyzed through graphical method as shown in Figure 3, which based on Vibration Time History as presented in figure 4. Notation “\( \alpha \)” represented the angle of ion direction to the horizontal axis. Ra, Rb, Rc and Rd show the resultant force of ion “a”; “b”; “c” and “d”. After being analyzed in 1.18 seconds of Vibration Time History, the angle position of ion “a” changed from 90° to 1.27°. Ion “b” changed from 60° to 1.86°. Ion “c” changed from 30° to
0.88°. Otherwise, ion “d” remained in its position as 0°. The final direction of the ionic collision was in the horizontal direction. The analysis proved that the ionic collision in random direction had been affected by the vibration to planar-horizontally direction in a few seconds. Ion “a” needed 1.00 second to achieve horizontal direction from its initial direction, otherwise, ions “b”; “c” and “d” needed 1.18; 1.00 and 0.06 second as listed in Table 3.

![Figure 3. Vector analysis of four arrays of a), b), c), and d) ion directions as the representations of the randomic directions](image)

![Figure 4. Vibration Time History (VTH) of 8 Hz frequency recorded by a computer program](image)
Table 3. Resultant and direction of four ions after being analyzed based on VTH (R in x10^{-23} N)

| Time (sec) | Vibration Direction | ion a (°) | Ra (x10^{-23} N) | ion b (°) | Rb (x10^{-23} N) | ion c (°) | Rc (x10^{-23} N) | ion d (°) | Rd (x10^{-23} N) |
|------------|---------------------|-----------|-------------------|-----------|-------------------|-----------|-------------------|-----------|-------------------|
| 0.06       | Left                | 21.5      | 19.53             | 28.8      | 18.32             | 16.43     | 14.49             | 0         | 12.8              |
| 0.12       | Right               | 10.2      | 38.55             | 13.4      | 38.08             | 6.7       | 35.13             | 0         | 33.8              |
| 0.18       | Left                | 6.6       | 59.35             | 8.6       | 58.74             | 4.18      | 56.04             | 0         | 54.8              |
| 0.24       | Right               | 4.9       | 80.24             | 6.4       | 79.56             | 3.04      | 77.00             | 0         | 75.8              |
| 0.30       | Left                | 3.8       | 101.16            | 5.1       | 100.46            | 2.38      | 97.97             | 0         | 96.8              |
| 0.36       | Right               | 3.1       | 122.11            | 4.2       | 121.32            | 1.95      | 118.95            | 0         | 117.8             |
| 0.42       | Left                | 2.6       | 143.08            | 3.6       | 141.28            | 1.65      | 139.94            | 0         | 138.8             |
| 0.48       | Right               | 2.3       | 164.04            | 3.1       | 161.24            | 1.43      | 160.94            | 0         | 159.8             |
| 0.54       | Left                | 2.0       | 184.21            | 2.75      | 181.21            | 1.26      | 181.93            | 0         | 180.8             |
| 1.00       | Right               | 1.8       | 204.32            | 2.45      | 202.20            | 1.13      | 202.92            | 0         | 201.8             |
| 1.06       | Left                | 1.6       | 224.24            | 2.22      | 223.17            | 1.02      | 223.92            | 0         | 222.8             |
| 1.12       | Right               | 1.4       | 265.07            | 2.03      | 244.17            | 0.93      | 244.91            | 0         | 243.8             |
| 1.18       | Left                | 1.27      | 286.07            | 1.86      | 265.15            | 0.88      | 256.91            | 0         | 264.8              |

The force of ionic collision also increased dramatically from its initial strength as shown in Table 3. The initial force of all ions were 8.2×10^{-23} N and then increased to 286.07×10^{-23} N; 265.15×10^{-23} N; 256.91×10^{-23} N and 264.8×10^{-23} N for ion “a”, “b”, “c” and “d” respectively. This phenomenon showed the agreement to the data of previous research in which CaCO$_3$ deposition rate increased and the induction time decreased by the presence of vibration. The direction uniformity of the ionic collision in planar-horizontal was an unusual phenomenon and does not occur in the environment, so, it needed more explanation.

The data showed that this planar-horizontal collision produced much more CaCO$_3$ deposition. To confirm this unusual phenomenon, an equation of product probability [23] as in Equation (8) was used.

$$P(\theta) = \left(\frac{\sigma_R}{2\pi}\right) G(\cos\theta)$$

Here, $P(\theta)$ described the product probability of density distribution in the scatter angle with the angle of attack $\theta$. $\sigma_R$ is the integral cross section. $G$ is the density of the product. As the equation and as a function of cosine, the product probability of the collision depended on the value of $\cos\theta$ of which the angle of $\theta$ could be scattered at 0° until 360°, as presented schematically in Figure 5.

![Figure 5. Schematic diagram of Ca and CO$_3$ ionic collisions in the angle of attack $\theta$](image-url)
The highest value of product probability was achieved when θ as 0° and 180° or in other temperatures was in horizontal position. When the cosθ achieved the maximum value, P (θ) as the product probability would reach the ultimate value. This would be the reason why ionic collision achieved maximally when the collision occurred in planar horizontally.

To distinguish the ionic collision between the vibrated and un-vibrated systems, a simple graph as shown in Figure 6 was used to express the ion distribution and ion direction. Figure 6a indicates that ion position in random configuration and collide in random direction. Figure 6b shows that ion position in a planar configuration and collide in horizontal direction. The ionic configuration of figure 6b which was plotted based on the vector analysis had been done and even the ionic configuration of Figure 6a was depicted as a usual phenomenon [12].

![Figure 6. Ionic collision of a) un-vibrated, b) vibrated system](image)

It is revealed that the planar horizontal direction as presented in Figure 6b brought the collision more effective than the random direction as shown in Figure 6a. At least there were two points of novelty of the research that had been found. First, the product probability of ionic collision was larger on the planar-horizontal direction. Second, the effective collision was easier to achieve as the data showed that the ionic force increased dramatically by the vibration. It only needed 1.18 sec to increase the ionic force from the initial stage until 35; 33; 32 and 33 times for ion “a”; “b”; “c” and “d”.

4. Conclusion

The research of ionic collision vector analysis on CaCO₃ precipitation based on vibration time history was successfully conducted. The ionic force was derived from its activation energy and there was 8.2×10⁻²³ N on every ion. Otherwise, the vibration force was calculated according to the data sent by the sensor and was found to be 21×10⁻²³ N. Normally, ion collides in a random direction, but vibration changed the ion collided in planar-horizontal direction. It was proved through vector analysis that the process needed only 1.18 sec. This study also confirmed that ionic force increased dramatically by the vibration and that is the reason why the vibration increased the deposition rate. Thus, the vibration mechanism in the affected CaCO₃ precipitation had been clearly justified.

5. References

[1] Kim B S, Kim Y K and Choi J 2008 Analysis of fluid-induced vibration of cryogenic pipes in consideration of the cooling effect J. of Mech. Sci. and Tech. 22 (2008) pp 2375-2385

[2] Sinir B G and Demir D D 2015 The Analysis of nonlinear vibration of pipe conveying an ideal fluid J. of Mech. Fluids 52 (2015) pp 38-44

[3] Oz H R 2001 Nonlinear vibrations and stability analysis of tensional pipes conveying fluid with variable velocity J. Non-linear Mech. 36(2001) pp 1031-1039

[4] Han X, Lin W, Tang Y, Zhao C and Sammut K 2015 Effects of natural frequency ratio on vortex induced vibration of a cylindrical structure J. Comp. & Fluids 110(2015) pp 62-76
[5] Li S J, Liu G and Kong W 2014 Vibration analysis of pipes conveying fluid by transfer matrix method Nuclear Eng. and Design 226(2014) pp 78-88
[6] Liang F and Wen B 2014 Force vibrations with internal resonance of a pipe conveying fluid under external periodic excitation. J. of Hydrodynamics, DOI:10.1016/S1001-5068 (14) 60086-X2014.
[7] Ruiz C, Jaramillo V H, Mba D, Ottewil J R and Cao Y 2015 Combination process and vibration data for improve condition monitoring of industrial system working under variable conditions. Mech. Syst. and Signal Proc. 66-67(2015) pp 699-714
[8] Andrew C, Hecimovich M and Nistor I 2015 Extrem wave loads on submerged water intakes in shallow water J. of Hydr. (2015)DOI:10.1016/S1001-6058(15)60454-1.2015,27(1)38-51
[9] Wolfram J and Naghipour M 1999 On the estimation of Morisson force coefficients and their predictive accuracy for very rough circular cylinders J. App. Ocean Res. 21(1999) pp 311-328.
[10] Laskovski D, Stevenson P, Galvin K P 2009 Lift and drag forces on an isolated cubic particle in pipe flow. Chem. Eng. Res. and Des, 87(2009); pp 1573-1581.
[11] Mangestiyono W, Muryanto S, Jamari J and Bayuseno A P 2015 The influence of vibration on CaCO3 scale formation in piping system The 3rd Bali Int. Sem. on Sci. and Tech, October15 2015. Denpasar Indonesia DOI: http://dx.doi.org/10.1051/matecconf/20165801027
[12] Chang R and Overby J, 2011 General Chemistry: The Essential Concepts, 6th edition, Mc. Graw Hill, New York.
[13] Marcus Y 2006 Ionic volumes in solution Biophys.1 Chem. 124 (2006) pp 200–207
[14] De S, Ghosh P N, Roy A and Safvan C P 2006 A setup for probing ion–molecule collision dynamics Nuclear Inst. and Met. in Phys. Res. B 243 (2006) pp 435–441
[15] Wang F, Xua X C, Honga X H, J. Wang H J and Goua B C 2011 A theoretical model for electron transfer in ion–atom collisions: Calculations for the collision of a proton with an argon atom Physics Let. A 375 (2011) pp 3290–3295
[16] Sheikoleslami 2000 Calcium sulfate fouling-Pretipitation or particulate : A proposed Composite model Heat Transfer Eng. 21-3(2000) pp 24-33
[17] Muryanto S, Bayuseno A P, Ma’mun H, Usamah M and Jotho 2014 Calcium carbonate scale formation in pipes: effect of flow rates, temperature, and malic acid as additives on the mass and morphology of the scale Proc. Chem. 9(2014) pp 69-76.
[18] Bots P, Benning L G, Rodriguez-Blanco J D and Roncal-Herrero T, Shaw S 2012 Mechanistic Insights into the crystallization of amorphous calcium carbonate (ACC), Cryst. Gr. and Des. 12(2012) pp 3806-3814
[19] Rodriguez-Blanco J D, Shaw S, Benning L G, 2015 A route for the direct crystallization of dolomite, American Min. 100(2015) pp 1172-1181
[20] Ukrainczyk M, Kontrec J, Babić-Ivančić V, Brečević L and Damir-Kralj D 2007 Experimental design approach to calcium carbonate precipitation in a semicontinuous process Powder Tech. 171(2007) pp 192-199
[21] Andritsos N and Karabelas A J 2003 Calcium carbonate scaling in a plate heat exchanger in the presence of particles I. J. of Heat and Mass Trans. 46(2003) pp 4613–4627
[22] Petrou A L and Terzidaki A 2014 Calcium carbonate and calcium sulfate precipitation, crystallization and dissolution: Evidence for the activated steps and the mechanisms from the enthalpy and entropy of activation values Chem. Geo. 381 (2014) pp 144–153
[23] He X, Wu VWKC, Han K, Hao C, Zhang Y 2015 Mechanism of the collision energy and reagent vibration’s effects on the collision time for the reaction Ca + HCl Comp. and Th. Chem. 1056 (2015) pp 1-10
Acknowledgments
This research was supported by the Ministry of Research, Technology and Higher Education of Republic of Indonesia. The author would like to thank to the staffs of Metrology and Instrumentation Laboratory of Industrial Technology Department, Vocational Education, Diponegoro University, for their help in the device calibration.