

Temperature-Induced Variations in Particle Adhesion and Frictional Properties in Liquid Environments

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Abstract

Temperature changes can significantly impact how particles stick to surfaces and move in liquid environments, affecting everything from industrial processes to biological systems. Hence, this study investigates temperature-induced variations in particle adhesion using an inclined plane setup. It examines how adhesion strength is influenced by liquid type, particle roughness, size, and van der Waals forces. As temperature increases, liquid density and viscosity decrease, reducing adhesion. A spherical particle is suspended in a liquid and separated from a solid plane by a distance, with van der Waals force estimated using a standard equation. The study also applies kinetic and dynamic friction laws, determining rolling friction at the angle of repose, where a particle begins to slide on the inclined plane. Results showed that smaller particles required higher inclination angles to roll. In water, particles with diameters of 0.4500 cm rolled at angles corresponding to $\sin\theta$ values of 0.0910–0.0940, while smaller particles (0.0135 cm) had a $\sin\theta$ of 0.2743. In ethanol, rolling occurred at lower angles, with $\sin\theta$ values ranging from 0.1300 (0.0190 cm) to 0.1895 (0.0140 cm). Ethanol's lower density (789.3 kg/m³) than water (998.2 kg/m³) allowed earlier sliding. Graphs confirmed van der Waals forces dominated adhesion, with linear regression validating the model. Hamaker coefficients, calculated from the data, fall within reported literature values and increase with temperature. Coefficients of friction decrease with temperature, ranging from 0.0680 to 0.0400 (Water) and 0.0480 to 0.0326 (Ethanol). These findings apply to biomedical engineering, microfluidics, and nanotechnology, where controlling adhesion and friction is essential for efficiency and performance.

Keywords

Adhesion, Ethanol, Liquid, Small Spherical Particles, Water

INTRODUCTION

Temperature significantly influences particle adhesion and frictional behaviour in liquid environments, affecting industrial applications such as lubrication, coatings, and fluid dynamics. Researchers have extensively examined these variations, shedding light on the interplay between temperature, viscosity, and adhesion forces. For instance, [1] investigated silica particle adhesion in aqueous environments under varying temperatures. Their study revealed that increasing temperature reduced adhesion forces due to decreased water viscosity and weakened hydrogen bonding. This finding aligns with the work of [2], who reported that higher temperatures reduce liquid cohesion, lowering friction between interacting surfaces.

In contrast, [3] examined ethanol-based lubricants and observed that rising temperatures enhanced molecular mobility, leading to lower frictional resistance. This observation agrees with [4], who found that polymer-coated surfaces exhibit reduced adhesion when subjected to heat due to increased chain flexibility. These studies reinforce the understanding that the frictional properties of liquids are temperature-dependent. A related study by [5] explored the impact of heat on the microstructure of lubricating greases. Their findings indicated that internal fibre networks within greases deteriorate at higher temperatures, leading to changes in viscosity and frictional behaviour. Furthermore, [1] analysed temperature-sensitive coatings and found that surfaces could transition from hydrophilic to hydrophobic states, affecting how particles adhered.

The techniques available for measurement of adhesion between particles and planar surfaces include the inclined plane [6], centrifuge methods, aerodynamic or hydrodynamic methods [6], [7], [8], and a gravimetric method [8]. While the centrifuge method is particularly suited for submicron particles, the inclined plane is one of the best methods for large spherical particles (greater than 2 μ m in diameter). Particle adhesion and the effect of temperature on particle adhesion are of interest for practical and theoretical reasons [8], [9]. It is of interest to investigate the particle adhesion at high temperatures. The need to investigate particle behaviour at solidification fronts [10], [11], [12], motivated this study of particle adhesion to surfaces. In the above references, particles were embedded in the melt of a suitable matrix, and solidification was induced in a horizontal direction, with a vertical solidification front. As these particles might either settle to the bottom of the cell or float to the top, friction of the particles at either the

bottom or the top of the cell could become a problem.

[13] studied the mechanism of interaction between solid aerosol particles. He carried out some supplementary experiments on the adhesion between solid bodies and between solid particles. He found out that water was the cause of adhesion under ordinary conditions, namely of three mechanisms (a) Capillary force (surface tension) in the case of comparatively thick films of water on insoluble solids, (b) inter molecular force (hydrogen bonds) between water molecules and OH groups in the solids in the case of comparatively thin (monomolecular) films on insoluble solids. (c) Coalescence by dissolution and precipitation in the cases of thin or thick water films on soluble solids. However, his experimental evidence did not clarify the role of electrostatic charge. He established that electrostatic attraction after contact contributes negligibly and that the main effect of electrostatic charge is that of a discharge current upon the mechanisms.

In letters to Nature by [8] on adhesion of Atmospheric Dust fall particles to glass solids, it was discovered that particles of atmospheric dust adhere strongly to solid surfaces, as can be judged by the persistence of their presence on automobiles, window ledges, and other familiar surfaces. They carried out several investigations in the laboratory for years on the adhesion of solid particles to various surfaces to clarify the pertinent influential physical and chemical characteristics of the particle, substrate, and ambient air. Several different groups in recent years have carried out further research on the works of [8] and have reported results of measurements on small particle adhesion.

It is evident that before the research and contributions made by [8], no notable efforts were made to measure the forces of adhesion between atmospheric dust fall particles and solid surfaces, nor was any investigation made that compels the solid surfaces. His discussion centred on four sections: (i) fundamental concept of adhesion, (ii) the nature of a solid surface, (iii) the physical properties of particles, and (iv) the comments on the various theories of particle adhesion to solid surfaces. The numeric example of adhesive forces as a function of particle sizes was well detailed. Studying these effects in Nigeria, where climatic variations influence engineering applications, helps develop heat-resistant lubricants, coatings, and manufacturing materials. Additionally, this research supports environmentally sustainable solutions by improving energy efficiency and reducing wear in mechanical systems. Given Nigeria's growing industrial and technological advancements, this study is essential for material innovation and performance optimisation across various industries.

PROCEDURE

The effect of temperature on the main forces responsible for the adhesion of small spherical particles to a substrate immersed in a liquid is a topic of interest. The strength of this adhesive bond may also depend on the nature of the liquid, particle roughness, size, shape, and nature of contamination present in the liquid, as well as the net van der Waals forces. Increasing temperature causes the molecules to move faster and loosen from each other, increasing volume as the liquid expands. The mass remains Constant, and thus, the density decreases. The decrease in density will lead to a decrease in the viscous force of the liquid and probably the interfacial free energy. Consider a spherical particle (1) of radius R , suspended in a liquid (3) and separated from a plane solid (2) by a distance (d) in an inclined plane, the van der Waals force (F) can be approximately determined using the expression:

$$F = \frac{A_{132}}{6d^2} R(1)$$

The van der Waals force is attractive if the Hamaker Coefficient is positive; if it is negative, it is repulsive.

Laws of Kinetic/Dynamic Friction

- i. The force of friction acts in a direction opposite to where the body tends to move.

$$\frac{F}{R_N}$$

- ii. The limiting dynamic friction coefficient $\frac{F}{R_N}$ is constant.
- iii. For moderate speeds, the force of friction, which acts opposite to the direction of motion, remains constant but decreases slightly with increased speed.

As the distance of separation from the solid plane increases, the angle of inclination increases, but when the body

begins to slide, the angle of inclination is equal to θ . Here, the α Angle of repose is defined as the angle at which a body begins to move or slide down the inclined plane.

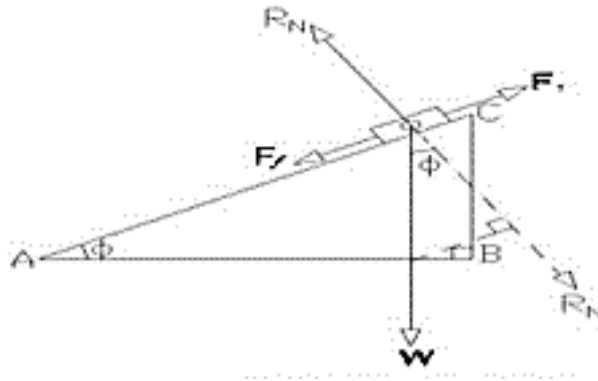


Fig. 1. The Inclined Plane

The rolling friction force is determined from the diagram above if sliding begins to occur.

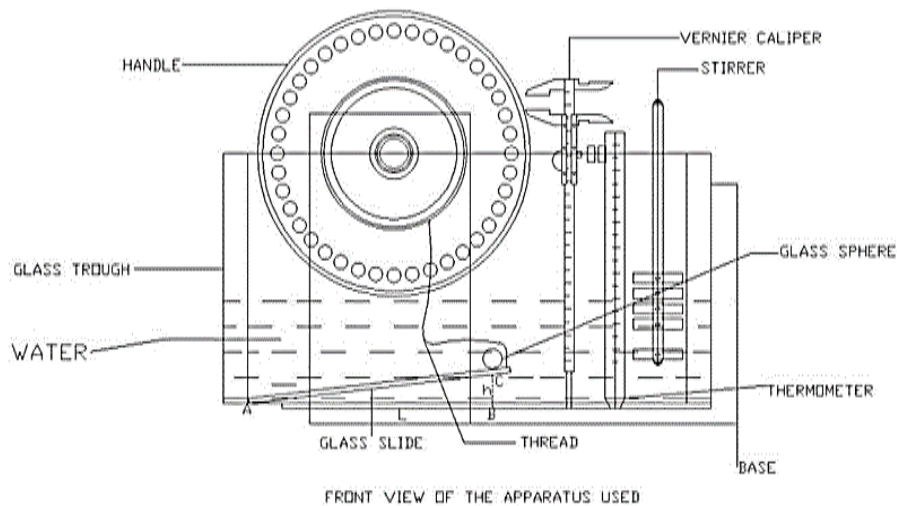


Fig. 2. Experimental Set-up

Schematic of the Experimental Setup

The inclined plane technique was chosen since it is ideal for large particle sizes, above $2\mu\text{m}$ in diameter. The experimental set-up is schematically given in Figure 2. It consists of a glass trough (100 x 100 x 50mm inner dimensions), which was also electrically heated to vary the temperatures of the matrix liquids (water or ethanol). These temperatures were monitored with a thermometer. The sizes of the glass spheres were measured and recorded using micrometer screw gauge just before the experiment. A metre rule was used to measure the horizontal position of a particle on a marked point on the surface of the glass slide (75 x 25 x 1mm). A lamp at the rear of the trough provided illumination. A wooden pulley assembly was designed to be manually operated, through which one end of the glass slide was raised. In contrast, the other end was pivoted at the inner edge of the trough until, at an angle of inclination, particles started to roll down the slide. The glass trough was filled two-thirds with the liquid, and then the glass spheres were deposited singly with tweezers at predetermined points on the surface of the substrate.

Experimental Procedure

The particles used were glass spheres ranging in size from 135 μm to 190 μm . Water was first used with large glass spheres, 1.9mm, 1.8mm, 1.7mm, 1.60mm, and 4.5mm in diameter as a test of the apparatus and procedure. Water and Ethanol were used as matrix liquids. Experiments were carried out with both sets of particles in water at room temperature, and in Ethanol maintained at the same temperature. The sizes and the initial positions of the particles were measured with micrometer screw gauge and meter rule respectively. As one end of the glass slide was raised slowly, the angle of inclination at which rolling of the glass particles occurred was determined by noting the final position of the particle. The angle ϕ was calculated from the expression $\sin \phi = h/L$, where h is the vertical distance through which the particle was lifted before rolling down, and L is the distance of the particle from the pivot measured on the surface of the glass slide.

The glass trough is made of a material 3mm thick with an internal dimension that is filled to two-thirds of the liquid. The glass sphere was deposited singly and guided to fall on a mark made on the plane just after its size was determined. The sizes of these glass spheres were measured and recorded at the beginning of the experiment. The handle of the wooden disc was turned gently to give a corresponding motion to the pulley to which the inextensible cord was attached from the plane. As the turning is on, the rotational motion of the pulley translates to a linear motion, which leads to a vertical increase in height (h) (measured from the bottom plate of the trough) of the inclined solid plane. When the particle begins to slide down the plane, the lifting of the plane is stopped, and the use of the meter rule determines vertical height while the parallax error is avoided. Thus, the angle of inclination (ϕ) is measured from the vertical height measured (h) and the length of the initial position of the spherical glass to the pivot (L). This procedure is undergone at different temperatures $\theta^\circ\text{C}$ with different sizes of glass spheres using two different liquids. Hence, the results are recorded and tabulated.

RESULT

The study examined the rolling behaviour of glass spheres in water and ethanol at room temperature, highlighting the impact of particle size and liquid properties on adhesion and friction. The first experiment was done with water at room temperature ($27^\circ\text{C} \pm 2$) and subsequently with Ethanol at room temperature. The data in Tables 1 and 2 present the angles at which rolling occurs for glass spheres of different diameters in water and ethanol at room temperature. In the case of water, for larger particles with a diameter of 0.4500 cm, the angles at which rolling begins, represented by $\sin \theta$, remain relatively low, ranging from 0.0905 to 0.0940. As particle size decreases, rolling requires a steeper inclination, with the smallest particle (0.0135 cm) rolling at an angle of 0.2743. This trend suggests that smaller particles adhere more strongly to the substrate. In agreement with [14], the results showed that smaller particles required steeper inclinations to roll, confirming that adhesion forces increase as particle size decreases. In contrast, [15] found that surface roughness also significantly influences adhesion, suggesting that irregularities in particle shape may contribute to the observed variations.

TABLE I. ANGLES FOR WHICH ROLLING OCCURS FOR WATER AS A TEST LIQUID FOR GLASS SPHERES AT ROOM TEMPERATURE

Particle Diameter D (cm)	L(cm)	h(cm)	1/R2 (cm-2)	$\sin \phi = h/L$
0.4500	3	0.27	19.75	0.0910
0.4500	4	0.38	19.75	0.0940
0.4500	5	0.45	19.75	0.0905
0.0190	3	0.55	110.80	0.1844
0.0165	3	0.59	146.92	0.1927
0.0155	3	0.81	16649.26	0.2692
0.0150	3	0.73	17776.89	0.2449
0.0135	3	0.82	21942.00	0.2743

For ethanol, the rolling angles also increase with decreasing particle size. The largest particle in this set (0.0190 cm) begins rolling at an angle of 0.1300, whereas the smallest particle (0.0140 cm) rolls at 0.1895. The angles in

ethanol are consistently lower than in water, indicating that rolling occurs more easily in ethanol. This aligns with the fact that ethanol has a lower density (0.7893 g/cm^3) than water (0.9982 g/cm^3), reducing adhesion forces.

TABLE II. ANGLES FOR WHICH ROLLING OCCURS WITH ETHANOL AS THE TEST LIQUID FOR GLASS SPHERES AT ROOM TEMPERATURE.

Particle Diameter D (cm)	L(cm)	h(cm)	1/R2 (cm-2)	$\sin \phi = h/L$
0.0190	3	0.39	11079.67	0.1300
0.0182	3	0.41	12075.84	0.1351
0.0170	3	0.47	13841.52	0.1582
0.0160	3	0.53	15625.00	0.1775
0.0150	3	0.53	17776.89	0.1772
0.0140	3	0.57	20408.98	0.1895

Tables 1 and 2 list the angles of inclination at which the glass spheres slid or rolled in water and Ethanol at room temperature. In the two cases, the general trend is an increase in the inclination angle at which rolling occurs, with decreasing particle size. The data are plotted in Figures 3 and 4, respectively. Scatter in these data may be due to irregularities in the shape of the glass spheres and imperfections of the substrate.

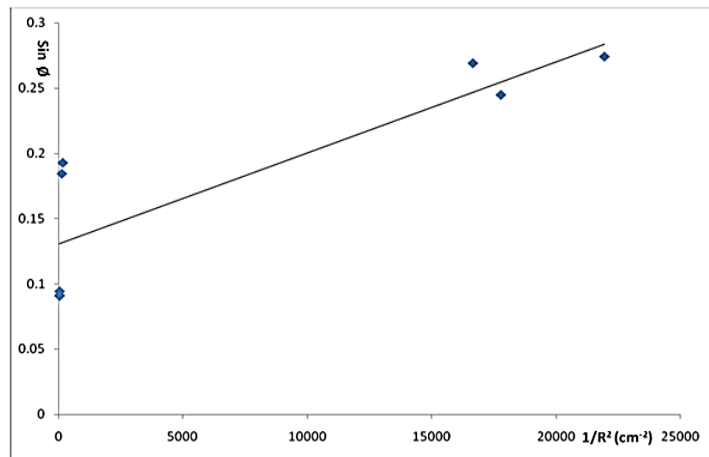


Fig. 3. The dependence of the angle of inclination ϕ at which rolling occurs on the particle's radius R, water is used as a matrix liquid at room temperature.

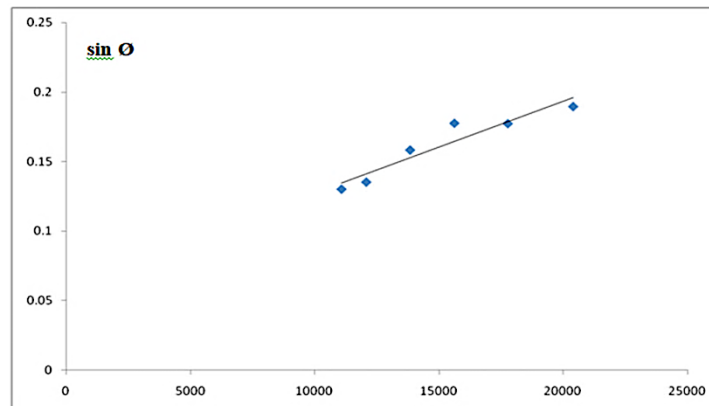


Fig. 4. The dependence of the inclination angle field, which rolls, on the radius R of the particle. Ethanol is used as a matrix liquid at room temperature.

The findings also showed that rolling occurred at lower angles in ethanol than in water, consistent with the lower density of ethanol (0.7893 g/cm^3) compared to water (0.9982 g/cm^3). This finding agreed with [16], who

demonstrated that liquids with lower densities exert weaker viscous forces, reducing adhesion. A related study [17] showed that van der Waals forces play a critical role in particle adhesion, and their study confirmed that adhesion forces are more pronounced in denser fluids. The density of pure water (0.9982g/cm^3 or 998.2kg/cm^3) is greater than that of Ethanol (0.7893g/cm^3 or 789.3kg/cm^3) at the same temperature, $20\text{ }^\circ\text{C}$. The angle of inclination was smaller in Ethanol than in water for the same type of particles. That is, given particles begin sliding earlier as the inclination angle increases in a less dense liquid. The larger the particles, the faster they will slide along the glass slide, hence the smaller the vertical height measured. This shows that the apparent weight of particles affects their adhesion to substrates.

It is interesting to plot our results in this form, which means that $\sin \phi$ is a function of the inverse of the square of the radius of the particles. The constants A and B denote the intercept on the y-axis and the slope of the Field graph against. The graphs for Water and Ethanol systems have been plotted. Each point represents an average of several values. Despite the scatter of the experimental results, the best fits for the experimental points are straight

$$\sin \phi = A + \frac{B}{R^2}$$

lines, which verifies the equation and validates the assumption that electrostatic effects were negligible in our systems. The straight lines drawn on the graphs plotted were obtained by linear regression. The positive slope of these lines shows van der Waals forces are attractive, and the particles will touch the solid substrate. This justifies the use of d_0 , the minimal distance between the particle and the substrate, instead of the variable distance d used in the equation above.

CONCLUSION

The angle of inclination at ambient temperature increased when the particle sizes were decreased, as shown in Tables 1 and 2. However, when the temperature was increased, the angle of inclination decreased for each particle size in both liquids, as shown in Tables 1 and 2. This shows that particle sizes affect adhesion. Smaller particles will adhere longer to the substrate than larger particles. The coefficient of friction decreased with increasing temperature, as shown in Tables 3 and 4, plotted in Figures 3 and 4. This shows that temperature affects the friction between a particle and a liquid matrix. Hence, increasing temperature reduces friction between the particle and the substrate. The Hamaker coefficients of the two systems studied at room temperature are between 10^{-14} mj/m^2 and 10^{-15} mj/m^2 . This would show a weak interaction in the interface.

When the temperature was increased, the Hamaker coefficient increased. This gave a positive slope when the graph of A_{132} vs T was plotted as shown in Figs. 3 and 4. When the Hamaker coefficient is positive, the van der Waals forces are attractive, but when it is negative, the force is repulsive. Since the values are positive, the van der Waals forces are attractive. But the increase. Surface tension affects the cohesion force between like particles of the exact nature and the adhesion between particles of different objects. In the case of glass spheres and the substrate, it was observed that at room temperature, the $\sin \phi$ values increased as the sizes of the glass spheres were decreased. But when heat was introduced, $\sin \phi$ values decreased with an increase in temperature. Therefore, most liquids increase in volume as their temperatures rise from $0\text{ }^\circ\text{C}$, so their densities diminish continuously; water and ethanol are no exceptions. When these liquids are heated, their densities decrease, their volumes increase, and their masses remain constant. The decrease in the angle of inclination in Ethanol is due to the decrease in density due to an increase in temperature, and the proximity to its boiling point.

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