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Topic 3.3: Solids, Liquids, and Gases

Worksheet · AP Chemistry

UNIT 3 · PROPERTIES OF SUBSTANCES AND MIXTURES

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How to Use This Worksheet

Work through the sections in order. Section A checks the ideas, Section B builds fluency with spacing, vapour pressure and boiling data, and Section C mixes everything in exam style.

One habit carries the whole topic: for any property, settle the spacing, the motion, and who is winning, kinetic energy or intermolecular forces. Most questions then answer themselves.

Do not look at the answer key until you have attempted every question. The key gives full working, so compare your reasoning, not just your final answer.

Section A: Recall and Concepts

A1. (a) For a solid, a liquid and a gas, state the spacing between the particles and the kinds of motion the particles have. (b) State which phases have a definite volume, which have a definite shape, and which can be compressed easily. (c) State which two phases are fluids, and name the particle motion that makes them able to flow.

A2. Samples of solid iron, liquid mercury and gaseous neon are all held at 298 K. (a) Compare the average kinetic energy per particle in the three samples. (b) A student says the neon atoms must

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carry the most kinetic energy, "because gas particles move fastest". Explain the confusion. (c) State two particulate level differences between the three samples that are real.

A3. (a) Name all six phase changes, and state for each whether energy is absorbed or released. (b) A beaker of ice and water sits at 0 °C while energy is steadily supplied. Explain why the temperature does not rise until the ice has all melted. (c) State what happens to the H_2O molecules themselves during melting, during boiling and during sublimation.

A4. (a) Define the vapour pressure of a liquid, describing the particle level events in a sealed container. (b) State the two things that determine a liquid's vapour pressure at a given moment. (c) Define the normal boiling point using vapour pressure, and explain why vapour bubbles can grow inside a boiling liquid but collapse in a merely warm one.

A5. (a) Define cohesion and adhesion. (b) Mercury forms rounded beads on glass, while water spreads over glass and rises in a narrow glass tube. Explain both observations. (c) State which of water and mercury has the higher surface tension, and explain what surface tension measures.

Section B: Core Practice

B1. One mole of water occupies about 18 cm^3 as a liquid. At STP the same mole occupies 22,400 cm^3 as a gas. The molar mass of water is 18.015 g/mol. (a) Calculate how many times larger the gas volume is than the liquid volume. (b) Treating the volume available to each molecule as a small cube, calculate the factor by which the centre to centre spacing between molecules grows when water vaporizes at STP. (c) Calculate the density of steam at STP, in g/cm^3. (d) A student writes: "Water molecules swell up when they boil, and that is why steam takes up so much room." Use your answers to correct the statement.

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B2. Vapour pressures at 25 °C: diethyl ether 537 torr, acetone 230 torr, ethanol 59 torr, water 23.8 torr. (a) Rank the four liquids by strength of intermolecular forces, strongest first, and justify the ranking. (b) Predict the order of the four boiling points, lowest first. (c) Calculate how many times larger the vapour pressure of ether is than that of water at 25 °C. (d) All four sit in a chamber at an external pressure of 500 torr, still at 25 °C. State which liquid boils, and justify your answer from the data.

B3. At 20 °C, the viscosity of water is 1.00 mPa·s and the viscosity of glycerol is 1,412 mPa·s. A glycerol molecule, $C_3H_8O_3$, carries three -OH groups. (a) Calculate the ratio of glycerol's viscosity to water's. (b) Explain, at the particle level, why glycerol is so much more viscous than water. (c) Predict what happens to glycerol's viscosity as it is warmed, and explain the change at the particle level. (d) A long chain oil with no -OH groups is still fairly viscous. State the second factor that raises viscosity.

B4. Two identical sealed syringes are prepared, one holding 120 cm^3 of air, the other 120 cm^3 of water. Both plungers are pushed hard. (a) State which plunger moves appreciably, and explain the difference at the particle level. (b) The air is compressed from 120 cm^3 to 30 cm^3 at constant temperature. Calculate the factor by which the volume falls, and the factor by which the average spacing between particles falls. (c) State what happens to the average kinetic energy of the air particles, and to their wall strike rate. (d) Explain why no realistic push can compress the water to 30 cm^3.

B5. Three particle diagrams describe the same substance in three phases. Diagram P: 20 particles in a regular grid, all touching, each with a short double headed arrow. Diagram Q: 20 particles, all touching but jumbled, arrows pointing assorted ways. Diagram R: 8 particles scattered across the whole box, each with a long arrow. (a) Assign each diagram to a phase, justifying each choice by

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spacing and motion. (b) A student redraws diagram R with the particles twice as wide, "because the gas has expanded". State the error, and what should have changed instead. (c) The substance in diagram P is warmed but does not melt. State the one feature of the diagram that should change, and one feature that should not.

B6. A sealed flask contains liquid ethanol in equilibrium with its vapour at 25 °C, where ethanol's vapour pressure is 59 torr. (a) State what equilibrium means at the particle level inside the flask. (b) The flask is warmed until the vapour pressure is 180 torr. Explain, at the particle level, why warming raised the vapour pressure. (c) At that same warmed temperature, the flask is connected to a pump holding the external pressure at 150 torr. State whether the ethanol boils, with a reason. (d) The flask then stands in open air at 760 torr. State what must happen to the vapour pressure before the ethanol can boil.

Section C: Exam Style

C1. Two liquids, X and Y, are compared at 25 °C. X has a vapour pressure of 537 torr and a surface tension of about 17 mN/m. Y has a vapour pressure of 23.8 torr and a surface tension of 72.8 mN/m. (a) State which liquid has the stronger intermolecular forces, giving both pieces of evidence from the data. (b) Predict which liquid has the higher boiling point, and which evaporates faster from an open dish. Justify each prediction. (c) Both liquids wet glass. Predict which climbs higher in a narrow glass capillary tube, and explain the prediction. (d) A student concludes that X must be made of larger molecules than Y, "because it escapes so easily". Evaluate the conclusion.

C2. On a high mountain the external pressure is 380 torr; water's vapour pressure reaches 380 torr at about 82 °C. A pressure cooker holds about 1,485 torr, where water boils at about 120 °C. (a) Explain why water boils at about 82 °C on the mountain. (b) An egg takes longer to cook in an open pan of boiling water on the mountain than at sea level. Explain why. (c) Explain why the pressure

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cooker cooks food faster than an open pan at sea level. (d) A camper says: "Water boils more easily up here, so cooking must be quicker." Identify the confusion in the statement.

C3. Four statements are made about phases. Evaluate each one: state whether it is right or wrong, and give the particle level correction. (a) "When water boils, the bubbles are hydrogen and oxygen gas, made when the molecules split apart." (b) "A gas compresses easily because its particles are soft and squash down smaller." (c) "The temperature stays constant during melting because no energy is being absorbed while it happens." (d) "A liquid keeps a definite volume because its particles are locked in fixed positions, like a solid's."

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Answer Key

A1. (a) Solid: particles in contact, held in fixed relative positions; the only motion is vibration about those positions. Liquid: particles in contact but not fixed; they translate, sliding and tumbling past one another. Gas: particles far apart, moving rapidly and randomly between collisions. (b) Definite volume: solid and liquid. Definite shape: solid only. Easily compressed: gas only. (c) The liquid and the gas; translational motion, the freedom to move past one another.

A2. (a) All the same: temperature fixes the average kinetic energy per particle, all three samples sit at 298 K, and phase makes no difference. (b) The statement mixes up motion with energy. Average kinetic energy per particle depends on temperature alone, not on phase or freedom of movement; where speeds differ, particle mass separates them, not extra energy handed to the gas. (c) Spacing: iron and mercury particles are in contact, neon atoms widely separated. Motion: iron atoms only vibrate in place; mercury and neon particles translate. Attractions steer mercury particles strongly, neon atoms barely at all.

A3. (a) Absorbed: melting, vaporization, sublimation. Released: freezing, condensation, deposition. (b) The supplied energy is spent loosening the solid's fixed arrangement against its attractions. None of it raises the average kinetic energy, and temperature measures average kinetic energy, so the temperature holds at 0 °C until melting is complete. (c) Nothing at all. The H_2O molecules stay whole and unchanged through all three changes; only their spacing, arrangement and motion change, and no covalent O-H bond is broken.

A4. (a) The pressure exerted by a liquid's vapour in a sealed container once equilibrium is reached. Particles continually escape from the surface, and vapour particles continually return; when the rates match, the vapour concentration and pressure stop changing. (b) The temperature, and the strength of the intermolecular forces within the liquid. (c) The normal boiling point is the temperature at which the vapour pressure equals 760 torr. A bubble inside the liquid is squeezed by the external pressure pressing through the liquid; it grows only when the vapour pressure inside matches that squeeze. Below the boiling point the vapour pressure falls short and bubbles collapse; at the boiling point they survive and grow throughout the liquid.

A5. (a) Cohesion is the attraction between particles of the same liquid. Adhesion is the attraction between a liquid's particles and a different material. (b) Mercury's cohesion, the metallic attractions between its atoms, far exceeds its adhesion to glass, so it pulls away from the glass into rounded beads. Water's adhesion to glass rivals its cohesion, so it spreads; at a wall, adhesion drags its edge up into a meniscus, and in a narrow tube the whole column rises: capillary action. (c) Mercury: 465 mN/m against water's 72.8 mN/m. Surface tension measures the energy cost of creating new surface area: the work of dragging particles from the fully attracted interior into the surface.

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B1. (a) 22,400 ÷ 18 ≈ 1,244 times larger. (b) Spacing grows by the cube root of the volume per molecule: the cube root of 1,244 is about 10.8, so molecules sit roughly 11 times farther apart, centre to centre. (c) Density = 18.015 g ÷ 22,400 cm^3 ≈ 8.0 × 10^{-4} g/cm^3. (d) The molecules are exactly the same size in steam as in liquid water. What grew is the empty space between them: spacing up about elevenfold in each direction gives the roughly 1,244 fold volume. Steam takes up room because it is mostly nothing.

B2. (a) Water strongest, then ethanol, then acetone, then ether weakest. Stronger forces hold particles in the liquid, fewer escape, and the vapour pressure is lower; vapour pressure ranks the forces backwards: water 23.8, ethanol 59, acetone 230, ether 537 torr. (b) Boiling point order is the vapour pressure ranking turned around: ether lowest, then acetone, then ethanol, then water. Measured values confirm it: 34.6, 56.1, 78.4 and 100 °C. (c) 537 ÷ 23.8 ≈ 22.6 times larger. (d) Ether only. Boiling needs vapour pressure to at least match external pressure; ether's 537 torr exceeds 500 torr, so it boils at 25 °C in the chamber, while acetone (230), ethanol (59) and water (23.8) fall short and stay liquid.

B3. (a) 1,412 ÷ 1.00 = 1,412: about 1,400 times as viscous as water. (b) Flowing requires molecules to slide past one another. Each glycerol molecule is fairly large and carries three -OH groups, so it hydrogen bonds to neighbours in every direction, building a dense network; every slide fights attractions on all sides. Water hydrogen bonds too, but its small molecules slip through far more easily. (c) It falls. Warming raises the average kinetic energy, so molecules more often slip out of each other's grip and the layers slide more freely. (d) Molecular size and shape: long chains tangle and drag as they slide.

B4. (a) The air plunger. Air particles are separated by large gaps, so the push mostly closes empty space. Water's particles are already in contact, with almost no gap to close, so its plunger barely moves. (b) Volume factor: 120 ÷ 30 = 4, the volume falls to a quarter. Spacing scales with the cube root of volume: cube root of 4 ≈ 1.59, so average spacing falls by a factor of about 1.6, to roughly 63% of its start. (c) Average kinetic energy is unchanged, because the temperature is constant. The particles strike the walls more often, each crossing the smaller space and returning sooner, so the pressure rises. (d) Squeezing water to a quarter of its volume would require its particles to overlap or squash; they are already in contact, and the empty space a gas offers is not there to remove.

B5. (a) P is the solid: particles touching in a regular grid, short arrows showing vibration about fixed positions. Q is the liquid: particles touching but disordered, arrows pointing assorted ways as they translate past one another. R is the gas: wide spacing and long arrows for fast, free motion between collisions. (b) The error is the particle size: particles are the same size in every phase. What should change on expansion is the spacing alone: spread the same sized particles through the larger volume. (c) Change: the vibration arrows grow longer, showing a larger amplitude. Not change: the grid positions; the particles keep their fixed arrangement until melting begins.

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B6. (a) Ethanol molecules escape from the liquid surface and vapour molecules return at equal rates, so the amount of vapour, and its pressure, stay steady. (b) Warming raises the average kinetic energy, so a much larger fraction of surface molecules carry enough energy to break free of the attractions; the escape rate climbs until balance returns at a higher vapour density, 180 torr. (c) Yes, it boils: the vapour pressure, 180 torr, exceeds the external 150 torr, so vapour bubbles can survive and grow inside the liquid. (d) The vapour pressure must climb until it equals 760 torr; the temperature at which it does so is ethanol's normal boiling point, 78.4 °C.

C1. (a) Y. Its vapour pressure is far lower, 23.8 against 537 torr, so far fewer of its particles escape the liquid; and its surface tension is far higher, 72.8 against about 17 mN/m, so creating surface in Y costs far more energy. Both measurements are priced by the attractions, and both say Y's are stronger. (b) Y has the higher boiling point: its vapour pressure starts far lower at 25 °C, so it must be heated much further before the vapour pressure can match the external pressure. X evaporates faster from an open dish: its vapour pressure shows far more of its particles escaping per second, and in open air they are carried away instead of returning. (c) Y climbs higher: both liquids wet the glass, so adhesion pulls both up, and the rise grows with surface tension; Y's is 72.8 ÷ 17 ≈ 4.3 times X's. (d) The conclusion does not follow. Ease of escape reports how strongly particles are held, not how big they are. Size works the other way: a larger molecule has more electrons and stronger dispersion forces, so large molecules tend to escape less readily. X's behaviour shows weak attractions, nothing more.

C2. (a) Boiling starts when the vapour pressure equals the external pressure. At sea level water must reach 100 °C for its vapour pressure to reach 760 torr; on the mountain the target is only 380 torr, reached at about 82 °C. (b) Cooking is done by the temperature of the boiling water, not by the boiling itself. On the mountain that water sits at about 82 °C instead of 100 °C, so heat passes into the egg more slowly and cooking takes longer. (c) The cooker traps steam until the pressure reaches about 1,485 torr, so the water cannot boil until about 120 °C. Food sits in water some 20 °C hotter than an open pan provides, and cooks faster. (d) The camper confuses boiling sooner with cooking faster. Mountain boiling starts cooler because the pressure is lower; cooking speed is set by how hot the water is, so cooking is slower.

C3. (a) Wrong. The bubbles are water vapour: H_2O molecules that escaped the liquid whole. Boiling overcomes the forces between molecules; it never splits one, and no hydrogen or oxygen forms. (b) Wrong. Gas particles do not squash; they are the same size as in any phase. Compression closes the empty space between them, which is why a gas, mostly empty space, compresses so far. (c) Wrong. Energy is absorbed all through melting; the temperature holds because that energy is spent loosening the particle arrangement against its attractions rather than raising the average kinetic energy, the only thing temperature measures. (d) Wrong. A liquid's particles are close but not locked: they translate past one another, which is why a liquid flows. The definite volume comes from attractions holding them close, not from fixed positions.

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