Question 1

10 points total | **Distribution of points**

(a)

i. 2 points

For showing the calculation of the force on the piston and a correct answer with units — 1 point

$F = PA = (1.0 \times 10^5 \text{ Pa})(5 \times 10^{-3} \text{ m}^2) = 500 \text{ N}$

For explaining the force in terms of gas atom collisions — some change in the atoms' momentum or velocity must be identified to justify a force between atoms and piston — 1 point

Example: The collisions of the gas atoms with the container walls cause a change in the momentum of the gas atoms, which means forces are exerted between the atoms and the piston. Each gas molecule colliding with a wall experiences a force from the wall that changes the molecule's velocity or momentum.

ii. 2 points

For showing the calculation of the temperature and a correct answer with units — 1 point

$PV = nRT$

$T = PV/nR = (1.0 \times 10^5 \text{ Pa})(0.10 \text{ m}^3)/(2)(8.31 \text{ J/mol•K}) = 602 \text{ K}$

For indicating that temperature characterizes the average speed or average kinetic energy or RMS velocity of the molecules — 1 point

(b)

i. 2 points

For identifying that the temperature increases due to increasing volume and constant pressure — 1 point

For relating temperature change with internal energy change — 1 point

Example: Because the volume increases at a constant pressure, the temperature goes up because $PV = nRT$. Increasing temperature means increasing average kinetic energy or total internal energy.

ii. 3 points

For calculating the work done in process *ABC* (i.e., the area under the line) — 1 point

$W_{AB} = -(1.0 \times 10^5 \text{ Pa})(0.10 \text{ m}^3 - 0.04 \text{ m}^3) = -6000 \text{ J}$ and $W_{BC} = 0$

For calculating T_A and T_C (or ΔT between the states) and using them to determine internal energy change — 1 point

$T_A = P_A V_A/nR = (1.0 \times 10^5 \text{ Pa})(0.04 \text{ m}^3)/(2 \text{ mol})(8.31 \text{ J/mol•K}) = 241 \text{ K}$

$T_C = P_C V_C/nR = (0.5 \times 10^5 \text{ Pa})(0.10 \text{ m}^3)/(2 \text{ mol})(8.31 \text{ J/mol•K}) = 301 \text{ K}$

$\Delta U = \Delta K_{\text{per molecule}} nN_0 = (3/2)k_B \Delta T nN_0$

$\Delta U = (3/2)(1.38 \times 10^{-23} \text{ J/K})(301 \text{ K} - 241 \text{ K})(2 \text{ mol})(6.02 \times 10^{23}) = 1500 \text{ J}$

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Question 1 (continued)

Distribution of points

(b)

ii. (continued)

Alternately, ΔU *can be calculated directly from the given data*

$\Delta U = (3/2)nR\Delta T = (3/2)(P_C V_C - P_A V_A)$

$= (3/2)\left(\left(0.5 \times 10^5 \text{ Pa}\right)\left(0.10 \text{ m}^3\right) - \left(1.0 \times 10^5 \text{ Pa}\right)\left(0.04 \text{ m}^3\right)\right) = 1500 \text{ J}$

For substituting ΔU and W (whether correct or incorrect) into some form of the first law of thermodynamics to find Q and for including units in a numerical answer — 1 point

$Q = \Delta U - W = 1500 \text{ J} - (-6000 \text{ J})$

$Q = 7500 \text{ J}$

(c) 1 point

For recognizing that the change in kinetic energy for process CA has the same numerical value as ΔU from (b)ii but with the opposite sign OR for calculating ΔK using the correct temperature change or $\Delta K_{\text{total}} = (3/2)nR\,\Delta T$ as shown below — 1 point

$\Delta K_{\text{total}} = (3/2)k_B \Delta T\, nN_0$ or $\Delta K_{\text{total}} = (3/2)nR\,\Delta T$

$\Delta K_{\text{total}} = (3/2)\left(1.38 \times 10^{-23} \text{ J/K}\right)(241 \text{ K} - 301 \text{ K})(2 \text{ mol})\left(6.02 \times 10^{23} \text{ mol}^{-1}\right)$

$\Delta K_{\text{total}} = -1500 \text{ J}$

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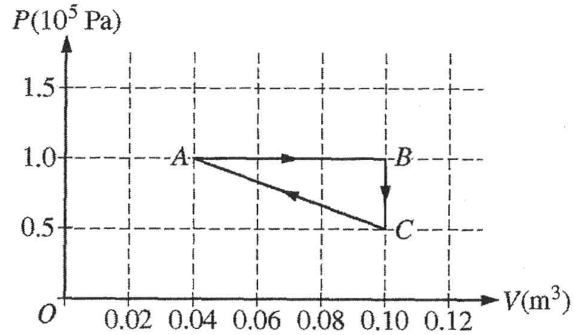
PHYSICS 2

Section II

4 Questions

Time—90 minutes

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.



1. (10 points, suggested time 20 minutes)
   Two moles of a monatomic ideal gas are enclosed in a cylinder by a movable piston. The gas is taken through the thermodynamic cycle shown in the figure above. The piston has a cross-sectional area of $5 \times 10^{-3}\ m^2$.

   (a)

   i. Calculate the force that the gas exerts on the piston in state *A*, and explain how the collisions of the gas atoms with the piston allow the gas to exert a force on the piston.

   $P = \frac{F}{A}$ $\quad F_A = PA = 1\times10^5\ Pa \times 5\times10^{-3}\ m^2$

   $F_A = 500\ N$

   The collisions of the gas atoms with the piston allow the gas to exert a force on the piston because the molecules are in rapid, random motion, and are frequently colliding with the walls of the cylinder and the piston. When molecules hit the piston in rapid, random motion, a force is exerted.

   ii. Calculate the temperature of the gas in state *B*, and indicate the microscopic property of the gas that is characterized by the temperature.

   $PV = nRT \quad T = \frac{PV}{nR} = \frac{1.0\times10^5\ Pa \times 0.10\ m^3}{2\ mol \times 8.31\ \frac{J}{mol K}}$

   $T = 602\ K$

   The average kinetic energy of the molecules of the gas is characterized by the temperature, and average kinetic energy relates to the microscopic property of the speed of the gas molecules.

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(b)

i. Predict qualitatively how the internal energy of the gas changes as it is taken from state A to state B. Justify your prediction.

The internal energy of the gas increases as it is taken from state A to state B because the pressure remains constant and volume increases, meaning that temperature increases. When temp increases, internal energy increases because $U = \frac{3}{2}nRT$.

ii. Calculate the energy added to the gas by heating as it is taken from state A to state C along the path ABC.

$\Delta U = Q + W$

$1496\,J = -6000\,J + Q$

$Q = 7{,}496\,J$

$\Delta U = \frac{3}{2}nR\Delta T$

$\Delta U = 1{,}496\,J$

$W = P\Delta V$

$W = 1\times10^5\,Pa \times 0.06\,m^3$

$W = -6000\,J$

$\Delta T = \frac{P_C V_C - P_A V_A}{nR}$

$\Delta T = 60\,K$

(c) Determine the change in the total kinetic energy of the gas atoms as the gas is taken directly from state C to state A.

$\Delta U = \frac{3}{2}nR\Delta T$

$\Delta U = \frac{3}{2} \cdot 2\,mol \cdot 8.31\,\frac{J}{mol K} \cdot 60\,K$

~~$\Delta U = 1496\,J$~~

$\Delta U = -1496\,J$

$\Delta T = T_c - T_A = \frac{P_A V_A}{nR} - \frac{P_C V_C}{nR}$

$\Delta T = \frac{0.5\times10^5\,Pa \times 0.10\,m^3}{2\,mol \times 8.31\,\frac{J}{mol K}} - \frac{1.0\times10^5\,Pa \times 0.04\,m^3}{2\,mol \times 8.31\,\frac{J}{mol K}}$

$\Delta T = -60\,K$

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PHYSICS 2

Section II

4 Questions

Time—90 minutes

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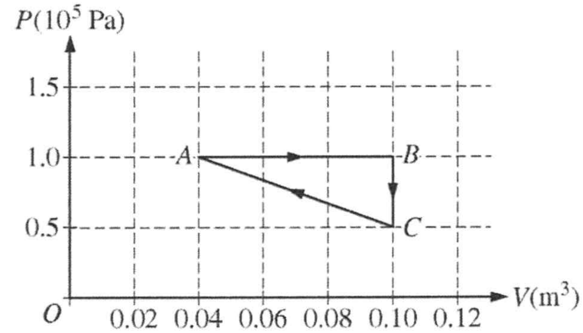

PV=nRT

1. (10 points, suggested time 20 minutes)
Two moles of a monatomic ideal gas are enclosed in a cylinder by a movable piston. The gas is taken through the thermodynamic cycle shown in the figure above. The piston has a cross-sectional area of $5 \times 10^{-3}\ \text{m}^2$.

(a)

i. Calculate the force that the gas exerts on the piston in state *A*, and explain how the collisions of the gas atoms with the piston allow the gas to exert a force on the piston.

$F = PA$

$F = (1\times10^5)(5\times10^{-3})$

$F = 500\ \text{N}$

Looking at the gas on a molecular level, you can see that the atoms are all moving around. Naturally, some of the atoms end up colliding with the piston. All of these collisions contribute together to an overall force that the piston feels.

ii. Calculate the temperature of the gas in state *B*, and indicate the microscopic property of the gas that is characterized by the temperature.

$PV = nRT$

$(1\times10^5)(.1) = 2(8.31)(T)$

$T = 601.6847\ \text{K}$

This temperature refers to the average kinetic energy of the atoms in the gas. In this case, the average kinetic energy would be $E_k = \frac{3}{2}k_bT = 1.245\times10^{-20}\ \text{J}$

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(b)

i. Predict qualitatively how the internal energy of the gas changes as it is taken from state *A* to state *B*. Justify your prediction.

Changing from A to B, the gas' pressure remains constant, while its volume increases. So, this means its temperature must decrease, since $\frac{PV}{T} = \frac{PV}{T}$. Since the temp. increases, the internal energy increases as well (since the total # of atoms remains constant).

ii. Calculate the energy added to the gas by heating as it is taken from state *A* to state *C* along the path *ABC*.

$\Delta U = Q + W$

$W = (1\times10^5)(.06) = -6000$ J

energy added (Q) equals 6000 J

$Q = \Delta U - W$

$Q = \Delta U + 6000$

(c) Determine the change in the total kinetic energy of the gas atoms as the gas is taken directly from state *C* to state *A*.

$E_K = \frac{3}{2} K_b T$

$\Delta E_K = E_{KC} - E_{KA} = \frac{3}{2} K_b T_c - \frac{3}{2} K_b T_A$

$PV = nRT$

$T_c = \frac{PV}{nR} = 300.842$ K

$T_A = \frac{PV}{nR} = 240.674$ K

$\frac{3}{2}(1.38\times10^{-23})(300.842) - \frac{3}{2}(1.38\times10^{-23})(240.674)$

$= 1.2454776\times10^{-21}$ J

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PHYSICS 2
Section II
4 Questions
Time—90 minutes

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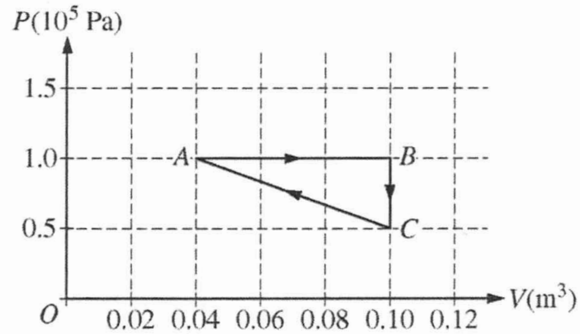

1. (10 points, suggested time 20 minutes)
Two moles of a monatomic ideal gas are enclosed in a cylinder by a movable piston. The gas is taken through the thermodynamic cycle shown in the figure above. The piston has a cross-sectional area of 5×10^{-3} m^2.

(a)

i. Calculate the force that the gas exerts on the piston in state A, and explain how the collisions of the gas atoms with the piston allow the gas to exert a force on the piston.

$F = \frac{P}{A} = \frac{(1 \times 10^5 \text{ Pa})}{(5 \times 10^{-3} m^2)} = 2.0 \times 10^7 N$

The gas particles collide with the movable piston exerting a force on it

ii. Calculate the temperature of the gas in state B, and indicate the microscopic property of the gas that is characterized by the temperature.

$PV = nRT$

$(1 \times 10^5)(.1 m^3) = (2)(8.31)(T)$

$T = 601.69 K$

Average kinetic energy of the molecules

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(b)

i. Predict qualitatively how the internal energy of the gas changes as it is taken from state *A* to state *B*. Justify your prediction.

Pressure remains the same and volume increases, therefore temperature increases as well because pressure and temperature are directly related

ii. Calculate the energy added to the gas by heating as it is taken from state *A* to state *C* along the path *ABC*.

$\frac{1}{2}bh$

$\frac{1}{2}(.1-.04)(1\times10^5-.5\times10^5)$

$= 1500J$

(c) Determine the change in the total kinetic energy of the gas atoms as the gas is taken directly from state *C* to state *A*.

@A $= (1\times10^5)(.04) = (2)(8.31)(T)$

$T = 240.67K$

@C $= (.5\times10^5)(.1) = (2)(8.31)(T)$

$T = 300.84K$

$300.84K - 240.67K = 60.17K$

Decreases 60.17K

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AP® PHYSICS 2
2016 SCORING COMMENTARY

Question 1

Overview

This question assessed learning objectives 5.B.4.2, 5.B.7.1, 5.B.7.3, 7.A.1.2, 7.A.2.1, and 7.A.3.3. The question assessed student understanding of the thermodynamic state properties and energy processes for a closed cycle of an ideal gas. The question asked students to make connections between microscopic and macroscopic properties of the gas.

Sample: P2 Q1 A
Score: 9

In part (a)(i) the force that the gas applies to the piston is correctly calculated and earned 1 point. The justification for why that force exists essentially repeats what the question states — that collisions cause the force — and earned no credit. Part (a)(ii) correctly calculates the temperature with units and indicates that it characterizes the average kinetic energy, which earned 2 points. Part (b)(i) correctly indicates increasing temperature, and explains it in terms of pressure and volume, and relates temperature to the change in internal energy, which earned 2 points. In part (b)(ii) 3 points were earned. The work done in process *ABC* is correctly calculated, the correct temperature change (calculated in part (c)) is used to determine the change in internal energy, and *Q* is correctly determined from these values using the first law of thermodynamics. Part (c) earned 1 point for indicating a value that is the negative of the internal energy change determined in part (b)(ii).

Sample: P2 Q1 B
Score: 5

Part (a)(i) has a correct calculation of the force the gas applies to the piston and earned 1 point. The justification essentially repeats what the question states — that collisions cause the force — and earned no credit. Full credit of 2 points was earned for part (a)(ii) because the correct temperature, including units, is calculated and correctly related to the average kinetic energy. Part (b)(i) correctly indicates that volume is increasing at constant pressure, but incorrectly states that this leads to decreasing temperature. The response then contradicts this statement by stating that the temperature increases. However, the response correctly concludes that a temperature increase means the internal energy increases, which earned 1 point. Part (b)(ii) correctly determines the work done by the expanding gas, which earned 1 point, but shows no calculation of an internal energy change and, therefore, has no value to substitute into the first law of thermodynamics. Part (c) contains a calculation of the change in kinetic energy for a single gas atom instead of the total kinetic energy of the gas atoms and determines the change going from *A* to *C* instead of *C* to *A*; therefore, no credit was earned.

Sample: P2 Q1 C
Score: 3

Part (a)(i) starts with an incorrect expression relating pressure, force, and area and then calculates an incorrect value for the force on the piston. The justification just repeats the question, so no credit was earned. Part (a)(ii) contains a correct calculation of the temperature at state *B* and correctly correlates temperature to the atoms' average kinetic energy, which earned 2 points. In part (b)(i) the response correctly indicates that the gas temperature increases with the expansion at constant pressure. However, nothing is stated about internal energy, so only 1 point was earned. In part (b)(ii) the area of the triangle is calculated, but it is not related to work or internal energy; therefore, no credit was earned. In part (c) the temperatures of the gas at states *A* and *C* are calculated along with the change in temperature, but there is no calculation of kinetic energy change, so no credit was earned.

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