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並不得書寫、畫記、作答。

國立清華大學 112 學年度碩士班考試入學試題

系所班組別：化學工程學系

科目代碼：0901

考試科目：輸送現象及單元操作

－作答注意事項－

1. 請核對答案卷（卡）上之准考證號、科目名稱是否正確。
2. 考試開始後，請於作答前先翻閱整份試題，是否有污損或試題印刷不清，得舉手請監試人員處理，但不得要求解釋題意。
3. 考生限在答案卷上標記「⬇由此開始作答」區內作答，且不可書寫姓名、准考證號或與作答無關之其他文字或符號。
4. 答案卷用盡不得要求加頁。
5. 答案卷可用任何書寫工具作答，惟為方便閱卷辨識，請儘量使用藍色或黑色書寫；答案卡限用 2B 鉛筆畫記；如畫記不清（含未依範例畫記）致光學閱讀機無法辨識答案者，其後果一律由考生自行負責。
6. 其他應考規則、違規處理及扣分方式，請自行詳閱准考證明上「**國立清華大學試場規則及違規處理辦法**」，無法因本試題封面作答注意事項中未列明而稱未知悉。

Problem 1 (20%)

Each sub-question is 2%

Fish is an excellent source of protein due to its lower fat and calories. A 100 g cooked fish can provide about a third of the average daily recommended protein intake. However, an inappropriate cooking process may affect the quality of eating because of protein denaturation and moisture migration. Thus, a well-control cooking process is necessary to maintain the nutrient in the food. Cooking fish in a conventional oven is a common cooking process, especially in the hotel and restaurant industries. To determine the properties needed for the prediction of heat and mass transfer during the cooking of fish, a numerical model for coupled heat and mass transport during the cooking of fish in a convection oven should be developed.

1. For the description of heat and mass transfer in the fish during the cooking process, which statement is NOT true?

   (A) Internal mass transfer is a pure diffusion process described by Fick's law and the pressure-driven transport of moisture in the muscle can be neglected.

   (B) Heat is transferred from the hot air to the surface of the fish by convection and radiation, and from the baking plate by conduction.

   (C) Mass transport through the fish is only driven by diffusion and convection.

   (D) Fourier's law of conduction can be used to model heat transfer in fish.

   (E) Convective boundary conditions are given by Newton's law of cooling.

2. The governing equation of heat transfer in the fish can be described by the following equation.

$$\rho c_p\left(\frac{\partial T}{\partial t}\right) = k\nabla^2 T - \rho_w c_{p,w} v_w \nabla \cdot T$$

   where ρ, c_p, and k are the density, specific heat, and thermal conductivity of fish, respectively. ρ_w, $c_{p,w}$, v_w are the density, specific heat, and flow velocity of water transported within the fish, respectively. Which statement is NOT true?

   (A) $k\nabla^2 T$ is the heat conduction term.

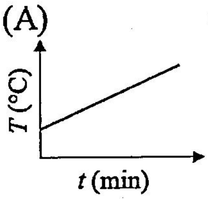
   (B) Thermal conductivity can vary with sample geometry.

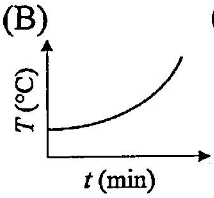
   (C) Radiative term is not considered in the governing equation.

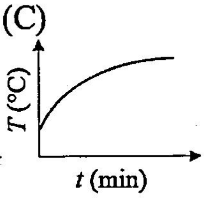
   (D) Viscous dissipation term is ignored in the system.

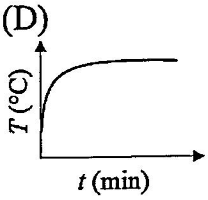
   (E) ∇ is the three-dimensional del operator.

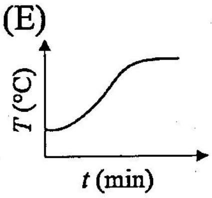
3. Please choose the correct temperature profile in the **geometric center** of the fish during the cooking process. t is the cooking time and T is the temperature.

(A) 

(B) 

(C) 

(D) 

(E) 

4. About the heat transfer in the fish, which statement is NOT true?
   (A) The unit of heat transfer coefficient is $W/(m^2 \cdot K)$.
   (B) Thermal conductivity of fish increases with temperature.
   (C) Biot number is the ratio of internal conductive resistance within the body to the external convective resistance at the surface of the body.
   (D) Brinkman number in this case is very large.
   (E) The unit of thermal diffusivity is the same as the mass diffusivity.

5. Heat transfer due to radiation should be considered during the cooking process. Please estimate the heat generation due to the radiation. Assume the surface temperature of the fish is 100°C, the oven temperature is 140°C, the emissivity of the oven is 0.9, the surface area of the fish is 48 cm^2, and the Stefan Boltzmann's constant is 5.676×10^{-8} $W/(m^2 \cdot K^4)$.
   (A) 0.07 W　(B) 2.4 W　(C) 48 W　(D) 1728 W　(E) 23875 W

6. The governing equation of mass transfer in the fish is based on the following equation.

$$\frac{\partial c}{\partial t} = D_w \nabla^2 c - \nabla \cdot v_w c$$

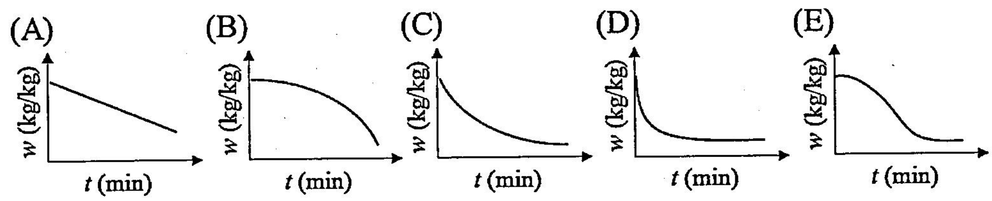
   where c and D_w are the moisture (water) concentration and moisture diffusion coefficient in the fish, respectively. Which statement is NOT true?
   (A) Water density is constant in this case.
   (B) Diffusion coefficient does not change with location.
   (C) The system only has free convection of mass transfer.
   (D) The system is able to reach a steady state.
   (E) $\nabla \cdot v_w c$ can be written to $v_w \cdot \nabla c$ when the density of water and diffusion coefficient are constant.

7. The flow velocity of the water in the fish is derived from the following equation.

$$v_w = -\frac{\kappa G'}{\mu_w} \nabla \left(w_w - w_{w,eq}(T) \right)$$

   where κ is the permeability of fish, G' is the storage modulus of the fish, μ_w is the dynamic viscosity of water, w_w is the mass fraction of water in the fish, and $w_{w,eq}$ is the water holding capacity of the fish as a function of temperature T. Which statement is NOT true?
   (A) The equation is derived from Darcy's law when the porous medium approach is applied.
   (B) The driving force of the equation is the difference in the temperature.
   (C) Water holding capacity decreases when the temperature increases.
   (D) Storage modulus increases when the temperature increases.
   (E) Viscosity decreases when the temperature increases.

8. Please choose the right mass fraction profile of fish during the cooking process. t is the cooking time and w is the mass fraction of the water in the fish.
($w = \dfrac{cM_w}{\rho_{fish}}$, M_w is the molecular weight of water).



9. About the mass transfer in the fish, which statement is NOT true?
(A) The unit of mass diffusivity is m^2/s.
(B) Mass diffusivity of water increases with temperature.
(C) Sherwood number is a dimensionless mass transfer coefficient that represents the ratio of the convective mass transfer rate to the mass diffusion rate.
(D) Péclet number can describe the ratio of momentum diffusivity and mass diffusivity.
(E) The unit of thermal diffusivity is the same as the mass diffusivity.

10. To obtain the weight loss of the fish, it is critical to obtain the evaporation rate. Please calculate the evaporation rate (w_{A0}) during the cooking process at isothermal condition. Assume the water mass faction is 0.8, the surface area of the fish is 48 cm^2, mass transfer coefficient is 0.001 m/s. The relative humidity is 0% and the water does not transport back to the fish.
Hint: $w_{A0} - w_w(w_{A0} + w_{B0}) = k_w A \Delta w_w$
(A) 0.192 m^3/s　(B) 0.294 m^3/s　(C) 0.54 m^3/s　(D) 1.024 m^3/s　(E) 1.42 m^3/s

Problem 2 (12%)

Each sub-question is 2%

Separation of isotopes by diffusion process

Tritium is an isotope of hydrogen with the formula H^3. It has a wide variety of uses in analytical chemistry, biology, and self-powered lighting devices. Isotopes are elements of identical chemical nature, hence separation by chemical methods is not feasible. One way of separating isotopes is by gaseous diffusion, *i.e.,* molecules of a lighter isotope would pass through a porous barrier more readily than those of heavier ones.

To calculate the diffusive flux, one must obtain knowledge on the diffusion coefficient of hydrogen (H_2^1) and tritium (H_2^3, or T_2) first. Assume that you are a scientist/engineer back in the era when the internet and smartphone do not exist. How would you proceed, with just your paper and pencil, to estimate the diffusion coefficients of hydrogen and tritium?

11. You probably would like to draw a qualitative picture on the diffusion of diluted gases first. From a molecular point of view, how does diffusion actually occur for gas molecules?

(A) The diffusion of gas molecules is driven by a pressure gradient. They flow from places of high pressure to regions of low pressure.
(B) The diffusion of gas molecules is driven by the van der Waals forces between individual molecules. The collective attraction forces resulted in a net movement of the molecules.
(C) The diffusion of gas molecules is driven by the random collision of molecules. The collective collision events resulted in a net movement of the molecules.
(D) The diffusion of gas molecules is driven by electrostatic interactions between the molecules. The attraction and repulsive interactions between the charged rubbing gas molecules resulted in a net movement of the molecules.

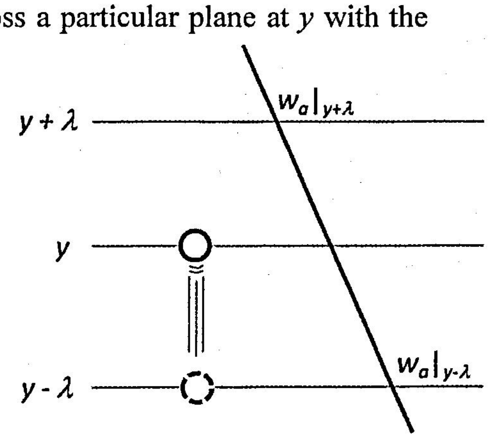
12. Good. Now, you start to think about how to describe the diffusion of gas molecules mathematically. To do so, you need some properties of the gas molecules and consider which ones, directly affect the diffusion behavior and therefore generate your mathematical formula.

(A) Number density (n), diameter (d), charge (z).
(B) Heat capacity (C_P), diameter (d), mass (M).
(C) Mass (M), diameter (d).
(D) Number density (n), mass (M).
(E) Number density (n), diameter (d), mass (M).

13. You also need some system parameters or constants to complete your description. From the list below, chose those that are required.
(A) Temperature, Reynolds number, volume.
(B) Pressure, Boltzmann constant, volume.
(C) Boltzmann constant, temperature.
(D) Reynolds number, temperature.
(E) Boltzmann constant, Reynolds number, temperature.

14. The number of gas molecules passing through a unit surface, *i.e.,* the diffusional flux, can be modeled by the mass balance across a particular plane at y with the simplified assumption that the gas molecules, on average, will meet another molecule after traveling a distance λ in space with a frequency of $n\bar{u}$ (where $\bar{u}$ is the mean molecular speed of the gas molecules).

If there exist a mass fraction (w_a) gradient of molecules of gas a, this means that the diffusional flux of gas molecules across the plane at y can be expressed by which of the following equation can be equated to Fick's first law of diffusion to solve for the diffusion coefficient?



(A) $j_a = -2n\bar{u}\lambda\frac{dw_a}{dy}$ (B) $j_a = -4n\bar{u}M\frac{dw_a}{dy}$ (C) $j_a = -2n\bar{u}M\lambda\frac{dw_a}{dy}$

(D) $j_a = -2\rho\bar{u}M\lambda\frac{dw_a}{dy}$ (E) $j_a = -4\rho\bar{u}M\lambda\frac{dw_a}{dy}$

15. The diffusion coefficient is therefore which of the following?
(A) $D_{aa} = 2n\bar{u}\lambda$ (B) $D_{aa} = 4\bar{u}M\lambda$ (C) $D_{aa} = 2n\bar{u}M\lambda$
(D) $D_{aa} = 2\bar{u}\lambda$ (E) $D_{aa} = 4n\bar{u}\lambda$

16. Now you know hydrogen diffuses faster than tritium by how many times?
(A) 1.414 (B) 1.732 (C) 2.000 (D) 3.000 (E) 4.000

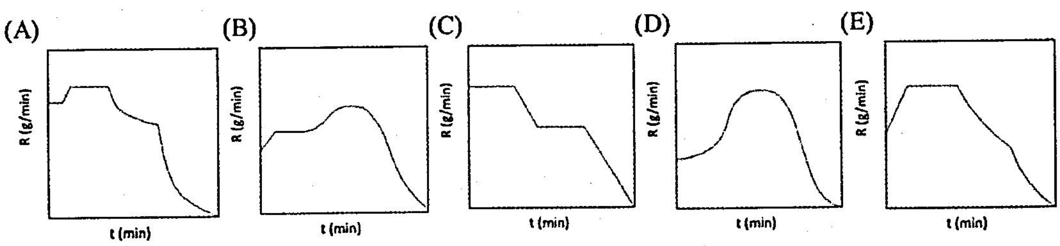
Problem 3 (8%)

Each sub-question is 2%

Drying of hydrated materials

Dehydration technologies are very important for the pharmaceutical and food industry. The shelf life of many related products can be greatly extended by their dry form after water removal.

17. Which of the following graphs best describes the evaporation rate over time for the hydrated (supersaturated) porous medium?



18. During the constant rate period, the system is essentially identical to which of the following?
(A) Evaporation of water droplets on a 200 °C pan.
(B) Evaporation of a puddle of muddy water after a rainy day.
(C) Evaporation of hot water that is placed inside a cup.
(D) Drying of a wet mop with the excess water already squeezed out.
(E) Evaporation of water droplets sprinkled from a nozzle into hot air.

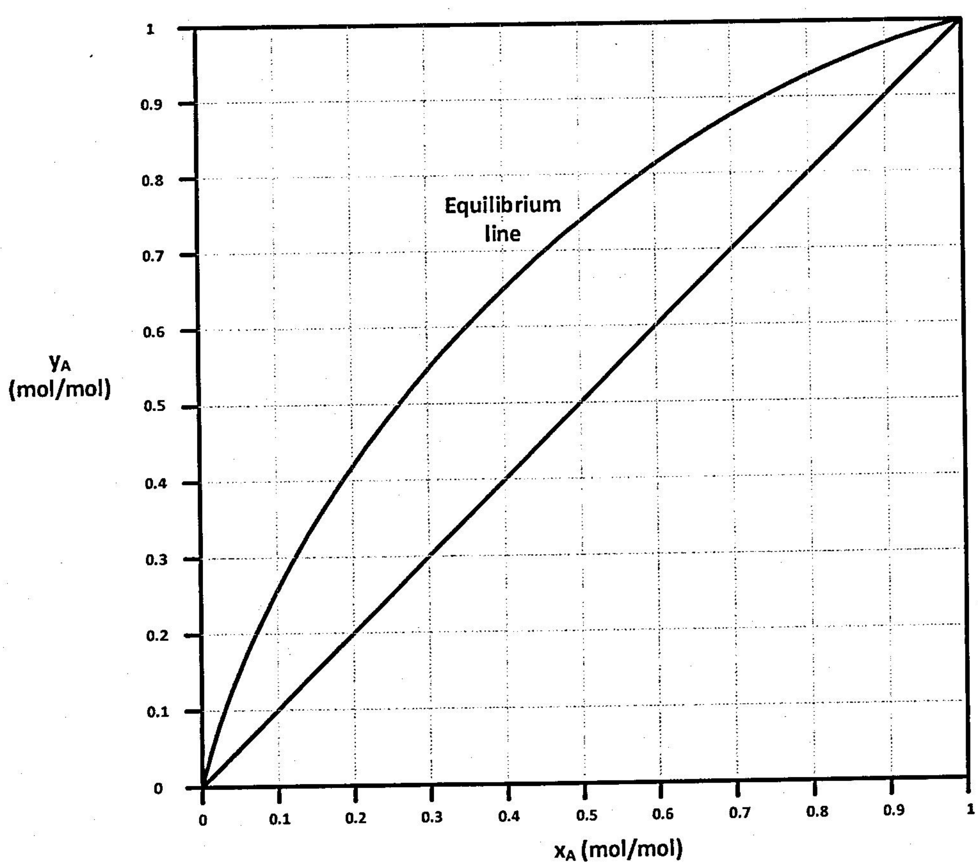
19. What is the rate of evaporation in the constant rate period if you are heating your hydrated material from 25 °C? (The input power is 1000 W. The specific heat capacity of the solid porous material is 2 J/g°C. The specific heat capacity of liquid water is 4.18 J/g°C and 1.9 J/g°C for water vapor. The latent heat of water evaporation is 2.256 kJ/g. The dry solid is 500 g and the wet solid is initially 1000 g).

(A) 1.36 g/s (B) 2.25 g/s (C) 0.18 g/s (D) 0.44 g/s (E) 0.96 g/s

20. To estimate the rate of evaporation in the constant rate period from a mass transfer point of view, what are the system parameters needed? **(multiple answers)**
   (A) Reynolds number of liquid water.
   (B) Temperature of the water.
   (C) Altitude.
   (D) Relative humidity of the air.
   (E) Rayleigh number of liquid water.

Problem 4 (15%)

A distillation column is designed to separate a feed that contains a binary mixture with 40 mol% of light component A. The mole fraction of light component A in the distillate should achieve 90 mol% and the heavy component in the bottom should achieve 90 mol%. The minimum reflux ratio has been estimated to be 0.8 with the given feed condition. Please use the equilibrium line in the figure below to answer the questions.



21. Based on the above information, what would the feed condition be? **(5%)**
   (A) Superheated vapor, (B) Superheated liquid, (C) Subcooled vapor,
   (D) Subcooled liquid, (E) Mixture of liquid and vapor.

22. The distillation column is operated at 1.5 times the minimum reflux ratio. How many ideal plates are at least needed to achieve the design specifications? **(5%)**

(A) 3 (B) 5 (C) 7 (D) 9 (E) 11

23. With the same reflux ratio in Q22, the feed condition has changed to saturated liquid. Please estimate how many plates can be reduced or should be added to achieve the design specifications. **(5%)**

(A) 1 reduced (B) 2 reduced (C) 1 added (D) 2 added (E) 3 added

Problem 5 (5%)

24. A heat exchanger was designed to heat a process liquid stream from 40 °C to 80 °C using saturated steam at 100 °C. The heat exchanger is operated at the designed conditions with the designed exchanger area and specifications. One day the flow rate of the liquid stream is reduced by 50% due to a process upset. What do you expect the outlet temperature of the liquid stream to be if the inlet temperature of the process liquid is unchanged? **(5%)**

Please estimate with the following assumptions:

- The overall heat transfer coefficient is dominated by the process liquid side and can be estimated by $U = CRe^{0.8}Pr^{0.33}$. The U is the overall heat transfer coefficient of the heat exchanger; the C is a constant; the Re is the Reynolds number; the Pr is the Prandtl number.
- All the physical properties of the liquid stream are temperature-independent
- The process liquid stream is in a single phase
- The saturated steam side is at a constant temperature of 100 °C

(A) 77 °C (B) 80 °C (C) 83 °C (D) 86 °C (E) 89 °C

Problem 6 (20%)

A fluid flows (along z direction) through a slightly tapered tube with the length L. The tube radius changes linearly from R_0 at the tube entrance to a slightly smaller value R_L at the tube exit. Assume that the Hagen-Poiseuille equation is approximately valid over a differential length, dz, of the tube so that the mass flow rate is

$$w = \frac{\pi[R(z)]^4\rho}{8\mu}\left(-\frac{dP}{dz}\right) \qquad (1)$$

where ρ and μ are the density and viscosity of the fliud, respectively, and P is the modified pressure.

(a) Write down the assumptions that were made in obtaining the Hagen-Poiseuille equation. **(5%)**

(b) Write down the expression for R as a function of z for the tapered tube. **(4%)**

(c) Change the independent variable in Eq. (1) to R, so that the equation becomes

$$w = \frac{\pi R^4\rho}{8\mu}\left(-\frac{dP}{dR}\right)\left(\frac{R_L-R_0}{L}\right) \qquad (2).\ \textbf{(5\%)}$$

(d) Integrate Eq. (2) to obtain an expression for the mass flow rate. **(6%)**

Problem 7 (10%)

Details of the calculation and justification are required for the answers.

Silica nanoparticles, with a mass concentration of 1.0% in weight and a bulk density of 2.0 g/cm^3, are dispersed in water (density of the aqueous solution: 1.0 g/cm^3). The total volume of the aqueous solution is 1.0 liter. Here, we use a small spray dryer to transform the silica nanoparticle aqueous suspension into dried and fine powder. The averaged diameter of the silica nanoparticles is 120.0 nm.

Here the flow rate of the air in the spray dryer is 2.0 L/min, and the transport length for the drying in the heating zone is 1.0 m. The diameter of the drying tube is 0.5 m. After 5 hours of spray drying, all silica nanoparticles in the aqueous solution convert into dried powder, with a free moisture content of < 0.00001 kg of H_2O/1 kg of silica nanoparticle.

(a) Please estimate the total number concentration of silica nanoparticles in the aqueous phase (unit: particles/cm^3 of solution). **(2%)**

(b) What are the retention time of the particle in the spray dryer **(1%)** and the average drying rate in this system, in term of kg of water per minute **(2%)**?

(c) Followed on (a-b): the particle concentration in aqueous phase can be effectively increased by up to 20 times using a centrifugation cleaning method (i.e., a mechanical separation process). What is the maximum total number concentration of silica nanoparticles in the aqueous phase after the centrifugation cleaning process? **(2%)**

(d) Instead of spray drying, we use a regular plate dryer to dry the concentrated solution having silica nanoparticles with a mass concentration of 20.0%. Due to the significant increase of the particle concentration, we should consider the critical moisture content. The critical moisture content is assumed to be 4 kg of H_2O/1 kg of silica nanoparticle, and the drying rate is linearly decay with water content. The area of drying is 1.0 m^2, and the drying rate at the critical point is 0.02 kg of H_2O/m^2·min. Do you expect to see a complete drying within 5 hours of operation (i.e., defined as the free moisture content < 0.00001 kg of H_2O/1 kg of silica nanoparticle)? **(3%)**

Problem 8 (10%)

Removal of airborne virus particle from the environment is important from the prospect of public health. Today, we evaluate one type of airborne virus particle electrostatic filter installed in the air conditioning facility. To simply the mechanism, we assume the filter is a small fixed-bed cylindrical filter. The diameter of the filter is 50.0 cm, and the length of the filter is 1.5 m. Also, the air flow rate is assumed to be constant at 10.0 L/min.

Knowing that more than 99% of the airborne virus particles can be assumed as sphere-like particle, and the diameter of these particles are 40-80 nm. Since the characteristics of these particles are similar, we assume the airborne virus particles are spherical with an averaged diameter of 60 nm. The density of the cylindrical filter is approximately 0.7 g of adsorbent/cm^3.

Using a butanol-based condensation particle counter, the number concentrations of the airborne virus particle eluting from the filter are recorded. Prior to the installation of this filter, the number concentration is 10^7 particles/cm^3. After installation, no particle eluted in the first 3 days. In Day 4, the concentration increased to be 2×10^5 particles/cm^3; In Day 5, the concentration is 5×10^5 particles/cm^3; In Day 6, the concentration is 1.0×10^6 particles/cm^3; In Day 7, the concentration is 5.0×10^6 particles/cm^3; In Day 8, the concentration is almost the same as the original without using the filter.

Based on the experimental data described above:

(a) Draw a breakthrough curve in term of relative/normalized number concentration of virus airborne particles eluting from the cylindrical filter versus the time of operation. **(2%)**

(b) Estimate the saturation capacity of the adsorbent (in terms of the number of virus particles/g of adsorbent). **(2%)**

(c) Estimate the fraction of the bed used when the number concentration of the airborne virus particle eluting from the filter is 1.0×10^6 particles/cm^3 (i.e., the breakpoint time is set at 6 days). **(2%)**

(d) Continued on (b-c): If the density of the virus particle is assumed to be the same as water, what is the saturation capacity of the adsorbent (in terms of g of virus/g of adsorbent)? **(2%)**

(e) The breakpoint concentration is changed to be at 3.0×10^6 particles/cm^3. What is the total number of virus particles eluting to the environment (i.e., not captured by the filter)? **(2%)**