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Design and Fabrication of an Activated Carbon Adsorber for The Treatment Of Borehole Water

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ABSTRACT
An activated carbon adsorber was designed using the scale-up approach for packed column design. The design parameters were used in the fabrication of the activated carbon adsorber. Three tests were carried out with the fabricated activated carbon adsorber on a given borehole water and system filtered water containing some impurities that has resulted to bad taste, odour, turbidity and colour to test run the efficiency of the adsorber. The results showed that the carbon adsorber performed relatively well in removing the bad taste, odour, turbidity, color and iron.
Keywords – Water; impurities; adsorber; taste, odour

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I. INTRODUCTION

It is stated that Water is a transparent, tasteless, odorless, and nearly colorless chemical substance, which is the main constituent of Earth's streams, lakes, and oceans, and the fluids of most living organisms [24]. It is vital for all known forms of life, even though it provides no calories or organic nutrients. There are two main sources of water: surface water (lakes, ponds, streams, rivers and storage reservoirs) and underground water (open wells, tube wells, artesian wells, springs and infiltration). Ground water is a major source of borehole water in most regions. According to many literatures [2]; [3]; [4]; [5]; [6]; [7]; [8]; [10]; [11]; [13]; [25], untreated borehole water contains many impurities. Theses impurities consist of suspended particles (fine silts and clays), biological matter (bacteria, plankton, spores, cysts or other matter) and floc. Some of the dissolved impurities or substances (like Iron, Manganese, etc) in the water may result to bad taste, odour, turbidity, colour, hardness, and excessive carbon dioxide, corroding concrete and metal parts in the distribution system. Both surface and underground water purification systems have many treatment stages. Typical water treatment processes and stages are shown elsewhere [16]; [25].

Filtration is a solid-liquid separation process in which the liquid passes through a porous medium to remove as much fine suspended solids as possible. Water or wastewater containing suspended matter is applied to the top of the filter bed. As the water (or wastewater) filters through the porous medium, the suspended matter in the fluid is removed by a variety of mechanisms. These mechanisms are: Straining, Sedimentation, Impaction, Interception, Adhesion, Adsorption, Flocculation, Biological growth. A detail work on these mechanisms, types of filtration and filter media are explained in literatures [2]; [16]; [25].

Adsorption is a process of adhesion of a liquid or/and gas on the surface of a solid [17]. It is also a natural process by which molecules of a dissolved substance collect on and adhere to the surface of an adsorbent solid. The adsorbent is the solid material onto which the adsorbate accumulates. The adsorbate is the dissolved substance that is being removed from liquid phase to solid phase and to the solid surface of the adsorbent. Adsorption is used in borehole water treatment to remove dissolved substances (such as iron, manganese, etc) which result to bad taste, odour, turbidity, colour, hardness, and excessive carbon dioxide, corroding concrete and metal parts in the distribution system. Conventionally, iron is removed from groundwater by the processes of aeration and rapid filtration. Different mechanisms may contribute to the iron removal in filters; flock filtration, adsorptive iron removal and biological iron removal. Which mechanism is dominant depends on the groundwater quality and the process conditions [1]; [14]. Iron present in anaerobic groundwater will be in the reduced state (Fe (II)). In the presence of oxygen, iron (II) will be oxidized to iron (III). The solubility product of iron (III) hydroxide is very low and hence the iron (III) will quickly hydrolyses to form iron (III) hydroxide flocks. Pin flocks are formed, that will grow depending on residence time. These flocks will subsequently be removed by filtration. The oxidation (1) and hydrolysis (2) reactions and the overall reaction equation are:

$4Fe^{2+} + O_2 + 2H_2O \rightarrow 4Fe3^{+} + 4OH^{-}$ (1.4)

$4Fe^{3+} + 4OH^{-} + (2x + 2) H_2O$
$\rightarrow 2(Fe_2O_3.xH_2O) + 8H^{+}$ (1.5)

The overall reaction equation becomes:

$4Fe^{2+} + O_2 + (2x + 4) H_2O$
$\rightarrow 2(Fe_2O_3.xH_2O) + 8H^{+}$ (1.6)

Oxidation and hydrolysis strongly depend on the pH. The reaction rate increases with increasing pH. The ions are adsorbed onto the catalytic surface of the filter media. Subsequently, in the presence of oxygen, the adsorbed iron (II) is oxidized forming a new surface for adsorption; in this way the process continues. The iron (II) adsorption capacity depends on the surface conditions of the filter material, the oxygen concentration and on the pH of the water. The capacity may also be influenced by other ions or organic matter present in the water (Mn^{2+}, Ca^{2+}, NH^{+4}). Calcium ions negatively affect the iron (II) adsorption [15]; [18]; [19]; [20]; [21]; [22]; [23].

Virtually every solid surface has the capacity to adsorb sorbate but the effectiveness of these solids in the wastewater treatment process is a function of its structure, degree of pola-rity, porosity and specific area. The adsorbate may be an organic compound with undesirable properties such as colour, odour, etc. The principal types of adsorbents include activated carbon, organic polymers and silica-based compounds and examples are listed [9]**.** Activated carbon is the usual adsorbent and is widely used in wastewater treatment processes due to its large surface area (up to 2000 m^2 /g) and its effectiveness for adsorption of a wide range of contaminants. However, activated carbon is expensive, not easily regenerated and largely restricted to the removal of non-polar materials, which limits its usage. Both types of activated carbon, granular and powder are made from a wide range variety carbonaceous, starting materials; coals (lignite, bituminous, anthracite), coconut shells, date stone, rice hull, seed shell, bamboo, saw dust, wood chips, corn cob and seeds, etc [3]. Characteristics of importance in choosing adsorbent types for adsorption include pore structure, particle size, total surface area, and void space between particles. Physical and electrochemical properties of adsorbent are tabulated in [9].

The aim of this work is to design an activated carbon adsorber for borehole water treatment systems to purify the untreated borehole water from the aeration/sedimentation tank before sending it to the treatment tank or to purify further the treated water from the water treatment tank in a water purification system. Figure 1 shows a typical borehole water purification system. The raw water from the ground (borehole) is taken by a water pump (submersible or surface) and it is sent to the open tank (aeration tank) through the open air for oxidation of iron and manganese. The water found in the open tank is toxic and contaminated as it is untreated. The untreated water from the open tank is sent to the treatment tank by gravity fall. The treatment tank contains sand, activated carbon and gravel in layers from the top to the bottom. The treatment tank is also chlorinated for further disinfection. Valves are attached at various points to control flow rate and direction. The efficiency in choosing the treatment techniques depends on the efficiency in reducing turbidity (97-99%), removal of viruses and bacteria (pathogens and protozoa) and other objectionable tasks and odor. Figure 2 shows the possible positions of the carbon adsorber (F). It is either placed immediately after the aeration tank for purification of the untreated water from the aeration tank before the treatment tank or it is placed after the treatment tank for further purification.

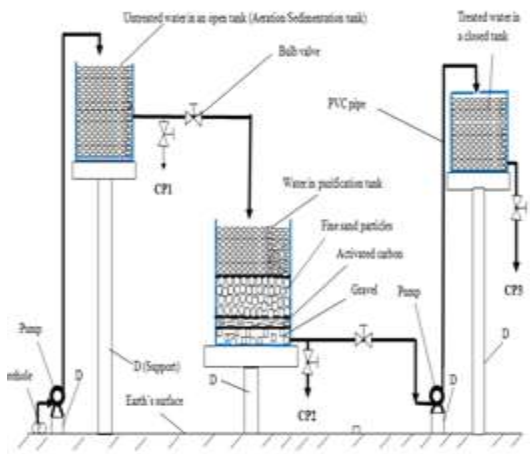

Figure 1. A simplified diagram of a borehole water purification system. CP1, CP2 and CP3 are water collection points. D is a support or stand.

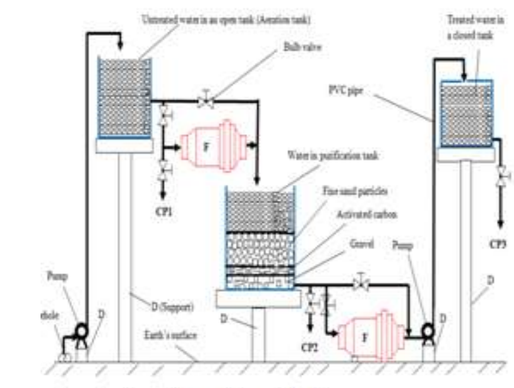

Figure 2. A simplified diagram of a borehole water purification system showing the possible positions of the Activated Carbon Adsorber (F).

II. METHODOLOGY

2.1. Activated carbon absorber design

The absorbability of an organic molecule increases with increasing molecular weight and decreasing solubility and polarity. This means that high molecular weight compounds with low solubility, such as most pesticides, are well adsorbed

2.1.1. Activated carbon choice

Firstly, it's important to remember that activated carbon can be used in different forms, basically, as powdered or granular. GAC (granular activated carbon) is utilized in drinking water treatment by installing it in a fixed bed adsorber. Water is passed through the adsorber containing the activated carbon which adsorbs organic compounds, purifying the water, while PAC (powder activated carbon) is used in a totally different way. It's added to water, mixed and then removed at the decantation or filtration stage. In this work the decision of using GAC instead of PAC is obvious because the work is to determine breakthrough behavior of micro pollutants in activated carbon columns.

2.1.2. Selection of a granular activated carbon

The next step is the selection of a granular activated carbon. There are a number of criteria that should be considered in this selection. GAC for this purpose needs a pore structure to allow the adsorption of a wide range of organic micro pollutants. The GAC must also possess a suitable amount of transport pores which allow the molecules to be transported to the adsorption site. The adsorption capacity for drinking water applications is very difficult to quantify by laboratory evaluation. Parameters such as the iodine number indicate the overall porosity of the carbon, but cannot be used to estimate the performance in drinking water applications. The design should be based on experience and references.

In general, the smaller the granule size, the better the adsorption performance, the effective size range is 0.6mm to 0.7mm. So parameters to be considered for the selection of a granular activated carbon are effective Size in mm; Iodine Number in min., mg/g; Methylene Blue Number in min; Abrasion Number in min; Moisture Content, as packed in max., %w/w and Mesh Size.

2.2. Design methods

2.2.1. Packed Column Design

It is not possible to design a column accurately without a test column breakthrough curve for the liquid of interest and the adsorbent solid to be used (figure 3).

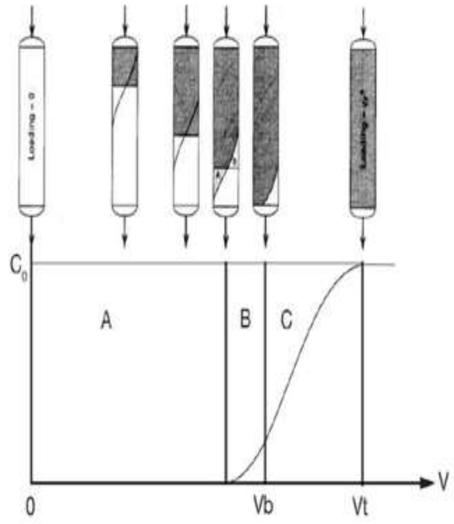

Figure 3. Theoretical Breakthrough Curve

There are two methods available to design adsorption columns: The Kinetic approach and Scale – up procedure. In both of the approaches a breakthrough curve from a test column, either laboratory or pilot scale is required, and the column should be as large as possible to minimize side – wall effects. Neither of the procedures requires the adsorption to be represented by an isotherm such as the Freundlich equation.

2.2.2. Kinetic Approach

This method utilizes the following kinetic equation

$$\frac{C}{C_0} \cong \frac{1}{1+e^{\frac{k_1}{Q}(q_0 M - C_0 V)}} \qquad (2.1)$$

Where

C = effluent solute concentration

C_o = influent solute concentration

k_1 = rate constant

q_o = maximum solid – phase concentration of the sorbed solute, e.g. g/g

M = mass of the adsorbent. For example, g

V = throughput volume. For example, liters

Q = flow rate. For example, liters per hour

The principal experimental information required is a breakthrough curve from a test column, either laboratory or pilot scale.

One advantage of the kinetic approach is that the breakthrough volume, V, may be selected in the design of a column.

Assuming the left side equals the right side, cross multiplying gives

$$1 + e^{\frac{K_t}{Q}(q_o M - C_0 V)} = \frac{C_0}{C} \qquad (2.2)$$

Rearranging and taking the natural logarithms of both sides yield the design equation

$$\ln\left(\frac{C_0}{C}-1\right)=\frac{K_1q_0M}{Q}-\frac{K_1C_0V}{Q} \qquad (2.3)$$

If $y = \ln\left(\frac{C_0}{C}-1\right)$, $b = \frac{K_1q_0M}{Q}$ and $mx = \frac{K_1C_0V}{Q}$, then

$$y = b - mx \qquad (2.4)$$

2.2.3. <u>Scale – up Procedure for Packed Columns</u>

- Use a pilot test column filled with the carbon to be used in full scale application.
- Apply a filtration rate and contact time (EBCT) which will be the same for full – scale application (to obtain similar mass transfer characteristics).
- Obtain the breakthrough curve.
- Work on the curve for scale up.

In this study, we are using the Scale – up Procedure for Packed Columns.

2.3. <u>Design equations using Scale – up Procedure for Packed Columns</u>

2.3.1. <u>Activated carbon effective size</u>

The first thing is the activated carbon effective size (0.7mm) and it is chosen based on literature [9] and suppliers.

2.3.2. <u>Diameter of the pilot plant</u>

The diameter (d) of the pilot plant is always assumed [4] when the activated carbon effective size is known. In this study, 4-inches diameter PVC pipe is used and so the assumed diameter is 4 inches diameter PVC pipe (0.1016m). A smaller diameter should not be selected in order to avoid excessive wall effects.

2.3.3. <u>Area of the Packed Column (A)</u>

The area is calculated taking into account that the column section is circular.

$$A = \pi r^2 \qquad (2.5)$$

A = Cross sectional area of packed column = πr^2; r = d/2, r is the radius and d is the diameter.

The area can also be calculated if the flow rate of packed column (Q) and Filtration rate of the pilot plant (FF) are known.

$$A = \frac{Q}{FR} \qquad (2.6)$$

2.3.4. <u>The Flow rate (Q) of The packed column</u>

The flow rate (Q) of the packed column can also be calculated from the linear velocity (u) and the surface area (A) as follows:

$$Q = uA \qquad (2.7)$$

The design value of the linear velocity should be between 5 and 20 m/h.

2.3.5. <u>Filtration rate of the pilot plant (FR)</u>

$$FR = \frac{Q}{A} \qquad (2.8)$$

$Q =$ Flow rate of pilot plant and $A =$ Cross sectional area of pilot plant = πr^2; r = d/2. Where r is the radius and d is the diameter.

FR of the pilot plant is the same as FR for Packed column.

2.3.6. <u>Empty Bed Contact Time of the Pilot Plant (EBCT)</u>

$$EBCT = \frac{V_{pp}}{Q} = \frac{V_c}{Q} \qquad (2.9)$$

Where
V_{pp} = Volume of the pilot plant = H x A = H x πr^2
V_c = volume of carbon
d_{pp} = is the diameter of the pilot plant
H = height of the parked column

$$V_{pp} = A\,x\,H = \pi\left(\frac{d}{2}\right)^2 x\ H \qquad (2.10)$$

EBCT for the pilot plant is the same EBCT of the Packed Column

2.3.7. <u>Height of the Packed Column</u>

The height of the packed column is the same as the height of the Pilot Plant. Because height is set by EBCT and Filtration rate, and these are the same for both Pilot Plant and the Packed Column.

2.3.8. <u>Mass of Carbon required in the Packed Column</u>

V_{pc} = Volume of the packed Column = Volume of carbon required = H x A_{pc} = H x πr^2
A_{pc} = Area of the packed column

$$V_{pc} = A\,x\,H = \pi\left(\frac{d}{2}\right)^2 x\ H$$

Packed bed carbon density is given by the supplier (Assume to be 400kg/m^3).

$$Density\ of\ carbon = \frac{Mass\ of\ carbon}{Volume\ of\ carbon} \qquad (2.11)$$

$$Mass = Density\ x\ volume$$

2.3.9. <u>Determination of q_e (Adsorbent removed)</u>

$$q_e = \frac{Adsorbate\ (TOC)\ removed}{Mass\ of\ carbon\ in\ the\ pilot\ column} \qquad (2.12)$$

2.3.10. <u>Fraction of Capacity Left Unused (Pilot Plant)</u>

Fraction of Capacity Left Unused (Pilot Plant)
$$= \frac{Total\ capacity\ - Adsorbent\ removed}{Total\ capacity} \qquad (2.13)$$

This fraction of capacity left unused will apply to the Packed Column also.

2.4 Calculation of design parameters

The design parameters calculation is based on the design assumptions and equations in section 2.3 and are presented in table 3

2.4.1. Activated carbon effective size

The activated carbon effective size chosen is 0.7mm.

2.4.2. Diameter of the pilot plant

The diameter (d) of the pilot plant assumed is a 4 inches diameter PVC pipe (0.1016m).

2.4.3. Area of the Packed Column (A)

The area is calculated taking into account that the column section is circular.

$A = \pi r^2 = \pi \frac{d^2}{4} = 3.142 \text{ x } \frac{(0.1016)^2}{4} = \mathbf{0.0081m^2}$

2.4.4. The Flow rate (Q) of the packed column

The flow rate (Q) of the packed column can also be calculated from the linear velocity (u) and the surface area (A) as follows:

$Q = uA = 20m/hr \text{ x } 0.0081m^2 = \mathbf{0.162m^3/hr}$

2.4.5. Filtration rate of the pilot plant (FR)

$FR = \frac{Q}{A} = \frac{0.162\,m^3/hr}{0.0081\,m^2} = \mathbf{20m/hr}$

FR of the pilot plant is the same as FR for Packed column.

2.4.6. Empty Bed Contact Time of the Pilot Plant (EBCT)

$$EBCT = \frac{V_{pp}}{Q} = \frac{V_c}{Q}$$

$V_{pp} = A \text{ x } H = \pi \left(\frac{d}{2}\right)^2 \text{ x } H = 0.0081 \text{ x } 0.15 = \mathbf{0.001215m^3}$

$EBCT = \frac{V_{pp}}{Q} = \frac{V_c}{Q} = \frac{0.001215\,m^3}{0.162\,m^3/hr} = \mathbf{0.0075hr}$

EBCT for the pilot plant is the same EBCT of the Packed Column

2.4.7. Mass of Carbon required in the Packed Column

Packed bed carbon density is given by the supplier (Assume to be 400kg/m^3).

$\text{Density of carbon} = \frac{\text{Mass of carbon}}{\text{Volume of carbon}}$

$\text{Mass of carbon required} = \text{Density x volume} = 400\frac{kg}{m^3} \text{ x } 0.001215m^3 = \mathbf{0.486kg}$

Table 3. Design Parameters

ACTIVATED CARBON:	
Effective Size	0.7 mm
Volume	0.001215m^3
Weight	0.486kg
COLUMN:	
Diameter	0.1016m
Area	0.00811m^2
Height of carbon bed	0.15 m
OPERATING CONDITIONS:	
Flowrate	0.162m^3/h
Linear Velocity	10 m/h
EBCT	0.0075hr

2.5. Materials for the proposed tubular filter pipe design

The proposed tubular filter media design is to be constructed using available PVC materials from water treatment stores or shops produced locally. The use of locally available material is important to ensure that the construction of the filter system is of low cost. The filter media both sand and gravel can be sourced locally.

2.5.1 Available Materials

The materials used for the proposed tubular filter pipe design are as follows:

1. 1 inch diameter Cylindrical PVC Pipe
2. 4 inches diameter Cylindrical PVC Pipe
3. 4 inches diameter Cylindrical PVC Pipe Union
4. 1 inch diameter pipe Unions
5. 4 by 1 inches diameters PVC Pipe Reducer
6. PVC Tape
7. PVC Gum
8. PVC Bulb Valve
9. Filter Net
10. Filter disc
11. Sand
12. Gravel
13. Activated Carbon

The pictures of the materials used are shown from figure 4-15. The design drawing for proposed the activated carbon adsorber is shown in figure 16.

Figure 4: 4 inches diameters Cylindrical PVC pipes

Figure 5: Cylindrical PVC pipe unions

Figure 6: 4 x 1 inch diameters PVC pipe reducers

Figure 7: PVC Tape

Figure 8: PVC Bulb Valve

Figure 9: PVC Gum

Figure 10: Filter disc

Figure 11: Filter net

Figure 12: fine Sand

Figure 13: Activated carbon

Figure 14: Hacksaw on a pipe

Figure 15: 1Hp water pump

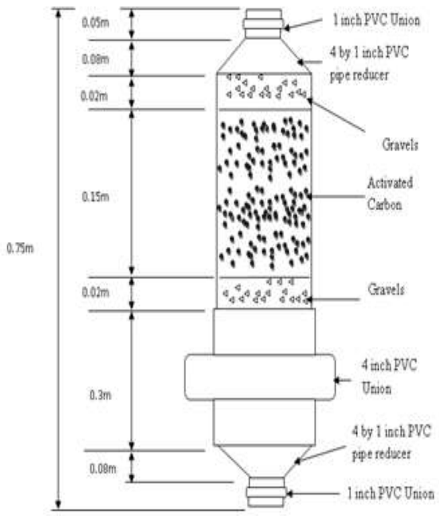

Figure 16. The design drawing of the Activated Carbon Adsorber Design

III. RESULT

3.1. Groundwater Test and Result

The purification process went through various tests to know the level of purity that has been achieved and the results were also compared with world Health organization (WHO) standards for water purification [WHO,2006]. Table 4 shows the results of water samples from the borehole (raw groundwater).

Table 4. Results from raw groundwater sample

S/N	Parameters	P/C Analysis	WHO Standard	Unit
1	General Appearance	Not clear with particles		
2	Taste	Objectionable	Unobjectionable	—
3	Odor	Objectionable	Unobjectionable	—
4	Temperature	30°C	Ambient	° Celsius
5	Turbidity	2.91	5	NTU
6	P^H Value	6.02	6.5 – 8.5	
7	Colour	Brown		
8	Total Hardness	123.40 (mg/l)	100	Mg/l
9	Total Alkalinity	41.06	200	Mg/l
10	Total iron	1.22	0.4	Mg/l

3.2. Purified water (without the use of activated carbon adsorber) Test and result

The purified water was also tested in the laboratory to know if it meets up with 'WHO' standard of purified water [WHO, 2006]. Table 5 shows the outcome of the results.

Table 5. Results from Treated groundwater sample

S/N	Parameters	P/C Analysis	WHO Standard (maximum permit)	Unit
1	General Appearance	Clear	Clear	
2	Taste	Unobjectionable	Unobjectionable	
3	Odor	Unobjectionable	Unobjectionable	—
4	Temperature	25°C	Ambient	° Celsius
5	Turbidity	0.00	5	NTU
6	P^H Value	7.48	6.5 – 8.5	
7	Colour	Colourless	15	TCU
8	Total Hardness	18.26 (mg/l)	100	Mg/l
9	Total Alkalinity	13.06	200	Mg/l
10	Total iron	0.01	0.3	Mg/l

3.3. Purified water (with the use of the activated carbon adsorber) test and result

The final stage of this work was carried out with the use of **the Activated Carbon Adsorber** and the result coupled together is shown in the table 6.

Table 6. Results from Treated groundwater sample with the Activated Carbon Adsorber

S/N	Parameters	P/C Analysis	WHO Standard (maximum permit)	Unit
1	General Appearance	Clear	Clear	
2	Taste	Unobjectionable	Unobjectionable	
3	Odor	Unobjectionable	Unobjectionable	—
4	Temperature	25°C	Ambient	° Celsius
5	Turbidity	0.00	5	NTU
6	P^H Value	7.00	6.5 – 8.5	
7	Colour	Colourless	15	TCU
8	Total Hardness	11.22 (mg/l)	100	Mg/l
9	Total Alkalinity	10.06	200	Mg/l
10	Total iron	0.01	0.3	Mg/l

IV. DISCUSSION AND CONCLUSION

Table 4 shows the results of water samples from the borehole (raw groundwater). Table 5 shows the outcome of the results after treatment but without **the Activated Carbon Adsorber**. Table 6 contains the result of the purification system with **the Activated Carbon Adsorber**. It is very clear as one compare and study the results from the tables 4-6 that the quality of the treated water with **the Activated Carbon Adsorber** show an improvement. More study will be done and reported in the next work for how long it will take for **the Activated Carbon Adsorber** to be cleaned or renewed. The portability of the activated carbon absorber makes this work so unique. It can be removed for cleaning very easily when dirty.

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