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Highlighting Specific Features to Reduce Chemical and Thermal Risks of Electronic Cigarette Use through a Technical Classification of Devices

Sébastien Soulet [1,*], Marie Duquesne [2], Charly Pairaud [1] and Jean Toutain [2]

1 Ingésciences, 2 Chemin des Arestrieux, 33610 Cestas, France; charly.pairaud@ingesciences.fr
2 Bordeaux INP, CNRS, I2M Bordeaux, ENSCBP, 16 Avenue Pey Berland, CEDEX, 33607 Pessac, France; marie.duquesne@enscbp.fr (M.D.); jean.toutain@enscbp.fr (J.T.)
* Correspondence: sebastien.soulet@ingesciences.fr

Featured Application: This publication provides an electronic cigarette classification based on physical characteristics and gives criteria to reduce risks of use.

Abstract: Currently, the emission generation protocol of electronic cigarettes has only one standardized vaping regimen that is consistent with mouth-to-lungs inhalation. Recent works show the significant increase in performance of the device with the use of a direct lung vaping regimen (167 mL s^{-1}, consistent with direct lung inhalation). However, requirements are needed for its use in a laboratory. This work aims at identifying mechanical characteristics of a device and providing a classification based on recommended power range, electrical resistance, heating surface, and air resistance of twenty-six tested devices. The electrical resistivity relation allows the estimation of the wire surface using its diameter and its length. The air resistance is obtained by measuring the pressure drop of the tested device with airflow rates ranging from 1–10 L min^{-1}. Through the wide panel of tested devices, results allow separating them in two categories: classical and sub-ohm electronic cigarettes consistent with the two inhalation behaviours. Differences up to 71 mm^2 for the wire surface and up to 4.8 Pa 0.5 min L^{-1} for the air resistance are observed between them. This limit seems to correspond to a required power of 25 W and an electrical resistance of 1.1 Ω.

Keywords: wire surface; heat flux; air resistance; vaping regimen

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1. Introduction

Electronic cigarettes (e-cigs) have been on the market for more than ten years. They have the same elements (Figure 1): an atomiser screwed or welded to a power unit. Atomisers are metallic cylinders with a coil unit that are sold empty. They are filled by a user with an e-liquid. In their design, the air inflow and aerosol outflow allow air circulation during the inhalation. The coil unit is also a metallic cylinder containing a resistive wire and a porous media draining the e-liquid from the tank (initial empty volume that is designed to receive and to stock the e-liquid) to the wire.

In the beginning, they had the same design as classical cigarettes. They were mostly made as a closed unit. The power unit used to deliver a fixed power was sealed to the rest of the device. Then, power units began to be screw-off and rechargeable. Following this innovation, adjustable power units appeared in the market. The power regulation had paved the way for the development of a wide panel of atomisers and e-liquids. More than 33,000 e-liquids and 6000 electronic cigarettes and accessories have been declared between 2017 and 2020 to the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) [1].

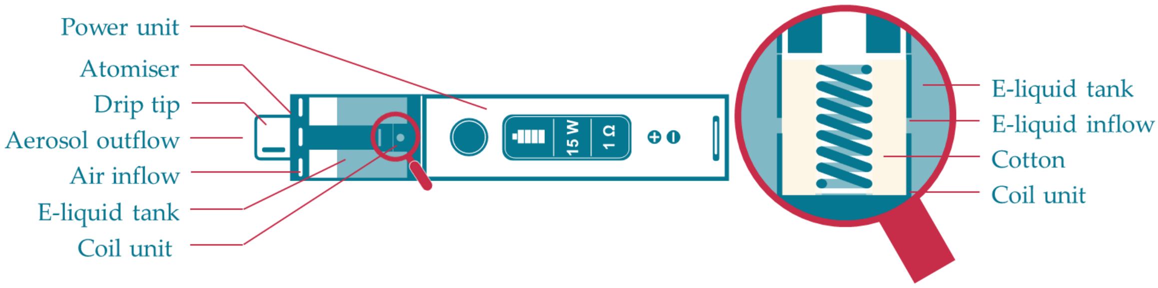

Figure 1. Scheme of an e-cig.

E-cigs are commonly classified by the generation of products mostly based on designed characteristics. Many descriptions are available but there are not standardized characteristics that allow an objective classification. In a publication, authors reviewed the current classifications available on the web [2] describing each category of products (Figure 2).

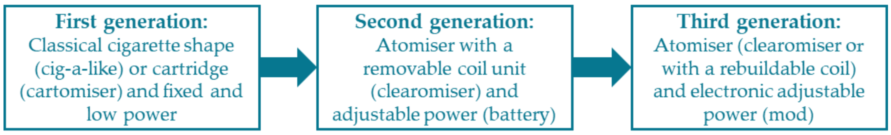

Figure 2. General characteristics of electronic cigarettes classification adapted from [2].

This classification mainly describes a story about the development of the devices since their apparition. Through this classification, there is not clear criteria allowing a strict classification of a device in a group.

Despite this wide market, the electronic cigarette function has not changed. As the user activates the power unit, an electrical current is delivered to the resistive wire. In response, the wire heats and vaporizes the surrounding e-liquid. The generated aerosol is finally inhaled by a consumer. So, e-cigs are devices using a thermal and thermodynamic phenomenon to generate an aerosol and depending on the e-liquid composition to deliver an active molecule such as nicotine. The variety of vaping products available (e-cigs and e-liquids) offers a large panel of configurations for a consumer.

The electronic cigarette functioning using standardized conditions was recently characterized [3]. According to the supplied power, three vaporization regimens were identified and described. At low powers, no aerosol is generated. This vaporization regimen is called under-heating. Increasing the power leads to the optimal regimen. In this one, the mass of vaporized e-liquid (MVE) according to the supplied power shows a linear trend. Then, above a power limit, this linearity is broken, and an over-heating regimen is reached. Consequently, the optimal regimen was characterized by two power limits: minimal and maximal powers.

In a recent publication [4], authors link these regimens to the produced aldehydes and highlight a significant increase in their productions using powers higher than the maximal power. They also suggest a link between the boiling process and vaping. The maximal limit would correspond to the critical heat flux. Consequently, wire surface is a key parameter that defines the limits of the optimal vaping regimen. By extension, knowing its value allow the determination of these limits and a requirement of power range with a lower chemical risk.

Additionally, we showed how vaping regimen (airflow rate) influenced the optimal vaporisation regimen [5]. The inhalation through an e-cig is commonly separated into two main behaviours (Figure 3): a mouth to lungs (MTL) or a direct lung (DL) inhalation. As illustrated, using MTL vaping regimen [6] reduces significantly the optimal vaporisation limits (lower minimal and maximal powers) and devices efficiencies. So, the power ranges required by a manufacturer of a sub-ohm devices would partially or totally be in an overheating regimen. It would present a more important chemical risk for the user. Consequently, understanding the technical characteristics relative of MTL or DL group of devices will improve their requirements under reduced risks for users. Additionally, we suggested the needed to define a standardized direct lung vaping regimen. It should be supported by technical requirements. Current classification does not allow an objective definition of these requirements. An aim of this publication is to provide these requirements.

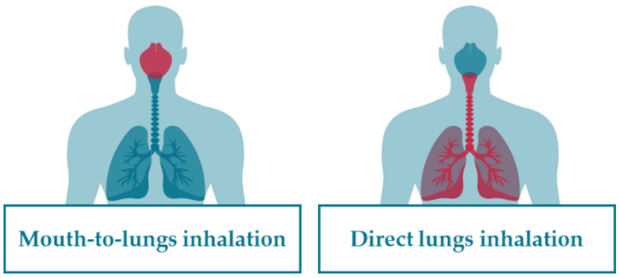

Figure 3. Mouth to lungs and direct lungs inhalations.

These two behaviours are identifiable through the respiratory organ filled by the generated aerosol. In MTL, users filled their mouth with the aerosol, stop vaping, and take a deeper inhalation in order to move the aerosol into the lungs. In DL, there is no stop, and the aerosol is directly moved into the lungs.

Additionally, in the inhalation mechanism, the inhalable or exhalable volumes by a human are linked to the pressure applied by the respiratory system. A typical pressure-volume diagram for a static human is presented in Figure 4. At a low pressure, lungs could be filled with air. However, they present a pressure limit below which the lung's capacities are close to zero. When a user inhales through a device, it generates a necessary pressure drop that decreases lung capacity.

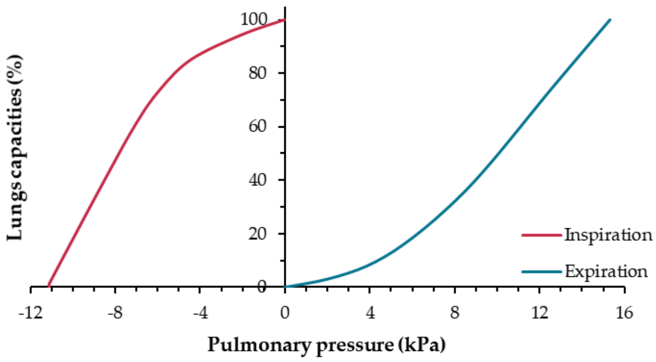

Figure 4. Pressure-volume diagram of breathing with the minimal inspiratory (red) and the maximal expiratory (blue) pressures adapted from [7].

A value of 10 kPa is medically accepted as a physical limit [8] below which a human could not inhale. Consequently, the pressure drop generated by a device is an important parameter in the understanding of inhalation behaviour. The parameter linking the pressure drop generated and airflow rate is called air resistance. It should also be a key characteristic that will modulate the inhalation and by implication the heat exchange with the wire.

This publication aims to provide a classification inspired from heat exchanger analyses [9,10] and to provide the technical criteria between MTL and DL requirements and between standardized and direct lungs vaping regimens use. Twenty-six devices are characterized. As the wire surface is the most central property, it is consequently the first series of experiments carried. The second series of experiments aimed to determine the air resistance generated by each device.

2. Materials and Methods

Twenty-six electronic cigarettes and atomisers are selected as a representative sample of the products available in the marked (Figure 5) and are tested.

Figure 5. Photography of the twenty-six tested e-cigs (**a**–**e**) and atomisers (**f**–**z**).

2.1. Electronic Cigarettes Tested

Their manufacturer and commercial names are listed in Table 1.

Table 1. List of the twenty-six tested devices.

Device Letter	Manufacturer	Commercial Name	Device Letter	Manufacturer	Commercial Name
a	BAT *	Blu Pro	n	Fumytech	Gotank
b	Joyetech	eRoll Mac	o	Vaptio	Cosmo
c	PMI **	Iqos Mesh	p	Vaporesso	Veco
d	JTI ***	Logic Pro	q	Eleaf	Melo III
e	JUUL	Juul	r	Innokin	I-Sub
f	Kangertech	Evod	s	Aspire	Cleito
g	Aspire	CE4	t	GeekVape	Zeus
h	Justfog	Q14	u	Uwell	Crown 4
i	Aspire	Nautilus	v	Titanide	Sub-Leto 24
j	Innokin	Jem	w	Hellvape	Fat Rabbit
k	Eleaf	GS Air	x	Smoktech	TFV8-Q4
l	Innokin	Prism T18	y	Kangertech	CL Tank
m	Joyetech	Cubis	z	Freemax	Fireluke 2

* British American Tobacco, ** Philip Morris International, *** Japan Tobacco International.

These devices present completely different designs. Among them, some are equipped with an internal power unit (Figure 2, devices a to e) and others should be connected to an external power unit. Some are larger or taller than others with different air inflow sizes (small holes in atomiser from Figure 2, devices a to k, lines in atomisers from Figure 2, devices l–z). Some devices, such as Cubis, are sold with several coil units. Our analysis is only made on the mainly used coil units. Due to their different design, additional coil units would have been considered as a completely new device. Technical information of the 26 devices provided by their manufacturers is synthetized in Table 2.

Table 2. Technical information provided by their manufacturers for the twenty-six devices—(N/A: Not Available).

Device Letter	Electrical Resistance (Ω)	Wire Metal	Porous Media	Power Range (W)	Inhalation Behaviour
a	1.8	N/A	N/A	9.1	N/A
b	1.5	Kanthal	Ceramic	9.1	MTL
c	1.8	N/A	N/A	7.6	N/A
d	1.8	N/A	N/A	7.6	N/A
e	1.6	N/A	N/A	8.5	N/A
f	1.5	N/A	Cotton	9.1	MTL
g	1.8	Kanthal	Cotton	5–13.9	N/A
h	1.6	Nichrome	Cotton	8–12	MTL
i	1.8	Kanthal	Cotton	9.8–13.9	MTL
j	1.6	Kanthal	Cotton	10–13.5	MTL
k	1.5	Kanthal	Cotton	8–20	MTL-DL
l	1.5	Kanthal	Cotton	14	MTL
m	1.0	SS 316L	Cotton	10–25	MTL-DL
n	0.7	Kanthal	Cotton	6–30	MTL
o	0.7	Kanthal	Cotton	15–23	MTL-DL
p	0.6	SS 316L	Ceramic	40–55	DL
q	0.5	Kanthal	Cotton	30–100	DL
r	0.5	Kanthal	Cotton	20–35	DL
s	0.4	Kanthal	Cotton	40–60	DL
t	0.4	Kanthal	Cotton	15–60	DL
u	0.4	SS 904L	Cotton	60–70	DL
v	0.2	N/A	Cotton	40–70	DL
w	0.2	Nichrome	Cotton	80	DL
x	0.15	Nichrome	Cotton	50–160	DL
y	0.5	SS 316L	Cotton	15–60	DL
z	0.15	Kanthal	Cotton	40–90	DL

Most of the devices are made with Kanthal wire used with cotton. However, Kanthal is a commercial brand and metals are named with an additional letter. The most used in e-cigs is Kanthal A and is considered as the one used in all these devices. Furthermore, devices look to be mainly designed for one type of inhalation behaviour. A global description of the different wire configurations that are observable through these devices is given in Figure 6.

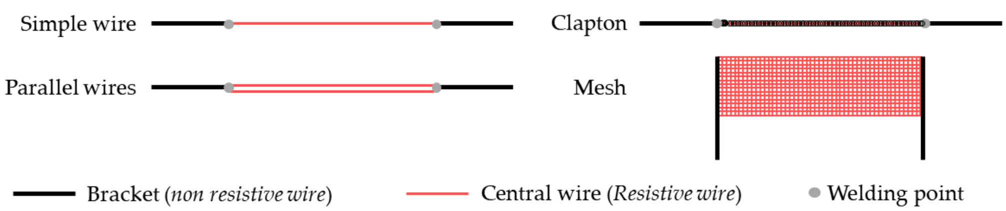

Figure 6. Scheme of the four heating elements designs extracted in the twenty-six tested devices.

Through the twenty-six electronic cigarettes tested, four types of set-up are observed. Each of them has brackets (non-resistive) that makes the electric connections with the power unit. Then, a central resistive part is welded to the brackets. The four types of set-up could be distinguished by their central part. They could be a simple wire or two parallel ones (GS Air, Prism T18, Cosmo, Melo III and TFV8) that are bare wires. Others have a central simple or parallel wire(s) that has a non-resistive wire rolled around, commonly named Clapton set-up (Cleito). Finally, the central part could be a mesh composed of the thinnest wires than the others set-up (Iqos Mesh, Zeus, Sub-Leto24, Fat Rabbit and Fireluke 2). An analysis of these manufacturer data is provided in the results sections. As electronic cigarettes are devices vaporizing an e-liquid, the first series of experiments carried out aims at measuring the wire surface of each tested device.

2.2. Wire Surface Measurement

The wire surface (S_w, in mm^2) is calculated using Equation (1).

$$S_w = D_w \cdot \pi \cdot L_w \tag{1}$$

with, D_w and L_w, the wire diameter (in m) and length (in m). The wire diameter presents a fastidious challenge. Wires are rolled inside an electronic cigarette. They have a curvature complicated to overhaul in order to obtain a straight line. Therefore, when they are extracted of a device in order to measure their diameters with a calliper, a slight curvature will remain during the measurement. The use of the electric resistance (R_w, in Ω), the electric resistivity of the metal (ρ_w, in Ω m) and the wire length allows overcoming this problem and determining the wire diameter using Equation (2) [11]:

$$L_w = \frac{R_w \cdot D_w^2}{4 \cdot \rho_w} \tag{2}$$

The electric resistivity obtained of the listed metal (Table 2) are reported in Table 3.

Table 3. Electric resistivity of the wire metals reported in Table 2.

Metal	Kanthal A	Kanthal A1	SS 316L	SS 904L	Nichrome
ρ_w(10^{-6} Ω m)	1.39 [12]	1.45 [12]	0.74 [13]	0.95 [13]	1.08 [14]

Then, the American Wire Gauge (AWG) standard is internationally used as a list of potential diameters. This standard defines a unit of diameter, applied in the wire manufacture. Table 4 provides the main correspondence between the diameters in AWG and in mm [15].

Table 4. Correspondence between the diameter in AWG and in mm.

AWG Diameter	26	27	28	29	30	31	32	33	34	35	36	37	38
mm Diameter	0.41	0.36	0.32	0.29	0.26	0.23	0.20	0.18	0.16	0.14	0.13	0.11	0.10

The method consists of, on one hand, measuring the unrolled wire length and, on the other hand, estimating lengths using Equation (2) and the wire diameters (Table 4). The real diameter is the one that minimizes the difference between the lengths measured and estimated. The determined diameter, length and surface are provided in the results section. The second series of experiments were aimed to determine the air resistance of the devices.

2.3. Air Resistance

The second parameter is the air resistance of a device (Ra, in $Pa^{0.5}$ min L^{-1}). It links the pressure drop generated (ΔP_a, in Pa) by a device for a given airflow rate (Q_a, in L min^{-1}). The type of experiments carried was also performed using medical inhalators [16,17] or classical cigarettes [18]. Air resistance is determined using Equation (3).

$$R_a = \frac{\sqrt{\Delta P_a}}{Q_a} \tag{3}$$

To obtain this value for each device, many airflow rates should be generated, and the corresponding pressure drops collected. To do so, a differential pressure sensor is used to measure the pressure drop at the drip tip when an airflow is generated using a mass flow regulator and a pump (Figure 7) as it is perceived during inhalation.

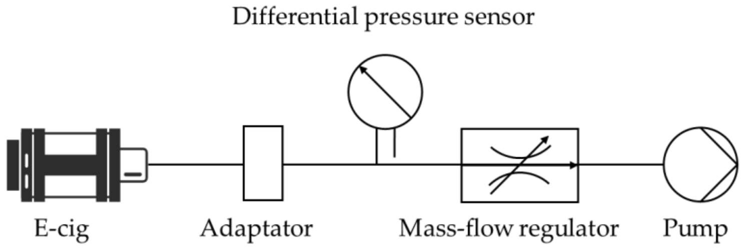

Figure 7. Experimental setup to carry pressure drop measurement.

Pressure drop are measured using an airflow rate between 1 L min^{-1} (standard vaping regimen) and 10 L min^{-1} (direct lungs vaping regimen) by step of 1 L min^{1}. A calibration experiment is firstly carried without connecting an e-cig (or atomiser). Then, the air resistance of the empty setup is obtained. It is finally subtracted from the other values measured when a device is connected.

3. Results

Results are presented following a list of parameters, the first of which is the recommended powers (fixed power or power ranges).

3.1. Power Ranges Analysis

Figure 8 illustrates the recommended powers of the twenty-six e-cigs and atomisers.

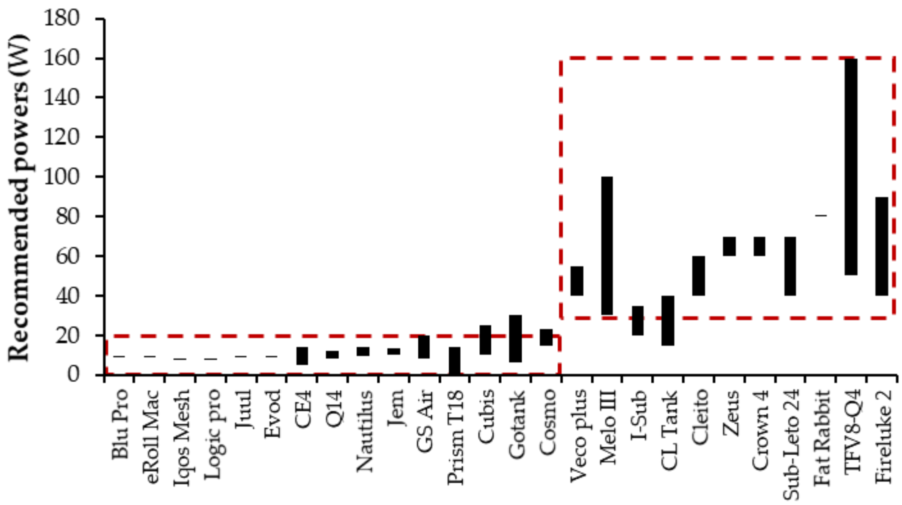

Figure 8. Recommended powers of the twenty-six tested devices.

Two main groups of devices emerge:

- a low power group with recommended powers below 20 W regrouping most of the fixed power e-cigs.
- a high-power group with recommended powers above 30 W. This second group could be used at higher powers and on a larger power range than devices of the first group.

However, some devices are recommended for powers mainly in one group and are able to go beyond these limits, such as Cubis, Gotank and Cosmo for the first group and I-Sub and CL Tank for the second one. Analysing more devices would allow a more precise determination between these two groups. Based on these devices, an average limit of 25 W will be used as a power limit. These two identified groups are systematically highlighted in the results in order to observe if they are identifiable with the mechanical characteristics.

3.2. Electrical Resistance Analysis

Figure 9 provides a graphical representation of the recommended powers and the electrical resistance for each device.

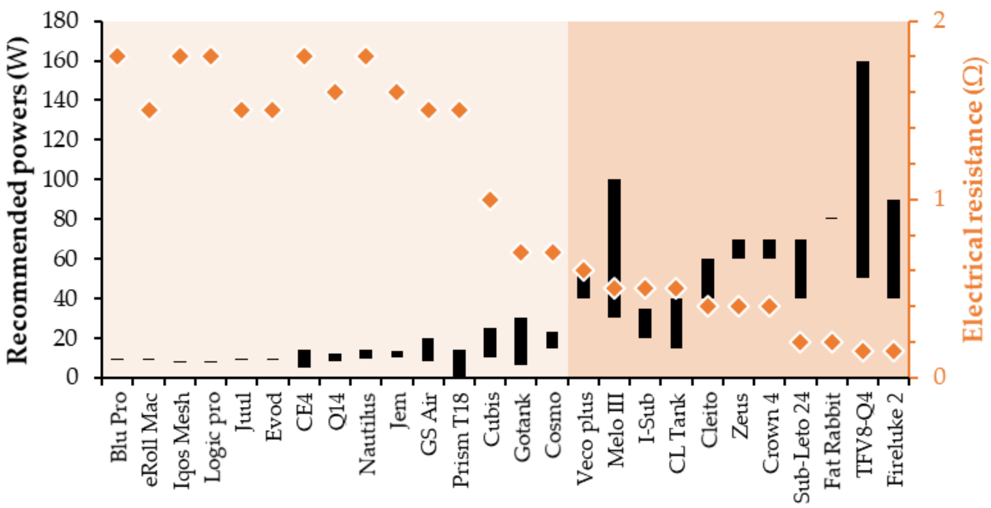

Figure 9. Recommended powers of the twenty-six tested devices regarding their electrical resistance values.

The two groups are also identifiable, but the limit is not between Cosmo and Veco plus but rather between Prism T18 and Cubis. From Blu Pro and Prism T18, e-cigs are designed for low powers with an electrical resistance higher than 1.5 Ω. Cubis looks to be an intermediate between the two groups. From the Gotank, devices are designed for higher powers with electrical resistance below 0.7 Ω. A limit between these two groups is 1.1 Ω.

3.3. Wire Surface

The dimensions (diameter and length) measured for the twenty-six devices and their calculated surfaces according to Equation (1) are reported in Table 5. However, Iqos mesh is not easily extractable without destroying its structure. Its dimensions could not be obtained correctly and are not provided. Zeus also has a mesh design, but the blades have a rectangular section.

Table 5. Wire electrical resistance, diameter, length, and surface of the twenty-six devices tested design as a simple wire, parallel wires, Clapton, or mesh.

Device Letter	R_w (Ω)	D_w (mm)	L_w (mm)	S_w (mm^2)	Device Letter	R_w (Ω)	D_w (mm)	L_w (mm)	S_w (mm^2)
Blu Pro	1.8	0.18	35	20	Gotank	0.7	0.32	41	41
eRoll Mac	1.5	0.16	21	10	Cosmo	0.7	0.23	39	56
Iqos Mesh	0.5	0.02	-	12	Veco	0.6	0.23	33	24
Logic Pro	1.8	0.18	32	18	Melo III	0.5	0.41	178	226
Juul	1.6	0.18	28	16	I-Sub	0.5	0.46	59	84
Evod	1.5	0.18	33	19	Cleito	0.4	0.46	47	134
CE4	1.8	0.18	40	23	Zeus	0.4	0.5 × 1.5	-	108
Q14	1.6	0.18	48	23	Crown 4	0.4	0.29	140	128
Nautilus	1.8	0.20	43	27	Sub-Leto 24	0.2	0.10	630	198
Jem	1.6	0.18	29	17	Fat Rabbit	0.2	0.20	496	311
GS Air	1.5	0.18	110	62	TFV8-Q4	0.15	0.20	308	188
Prism T18	1.5	0.18	106	60	CL Tank	0.5	0.41	418	131
Cubis	1.0	0.26	67	54	Fireluke 2	0.15	0.10	88	112

Wire diameters are lower than 0.20 mm for devices with electrical resistance upper of 1.5 Ω. Therefore, mesh devices that have electrical resistance below 0.5 Ω, also present wires with thin diameters, but the lengths are longer than previous wires. Due to their design, meshes have significantly higher surfaces. The wire surfaces are graphically represented in Figure 10 in regard to the recommended powers.

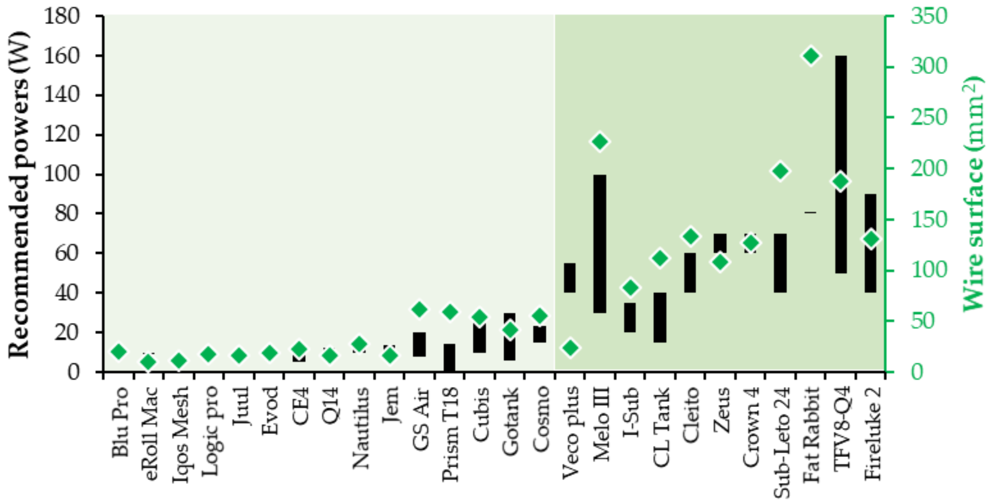

Figure 10. Recommended powers of the twenty-six tested devices regarding their surfaces.

The wire surface have a wide range of values (between 10 and 350 mm^2). Therefore, fifteen surfaces are between 10 and 62 mm^2 with nine values between 10 and 27 mm^2. In the other side, ten ones are upper than 80 mm^2 and are more dispersed. An average surface limit between 62 and 80 mm^2 is 71 mm^2. Additionally, wire surface and recommended powers looks correlated. In thermal problem, heat flux expresses the ratio between a power and the heat surface and characterizes the heat transfers. Following this observation, Figure 11 shows the average heat flux determined using the average recommended power and the heat flux range represented as a deviation.

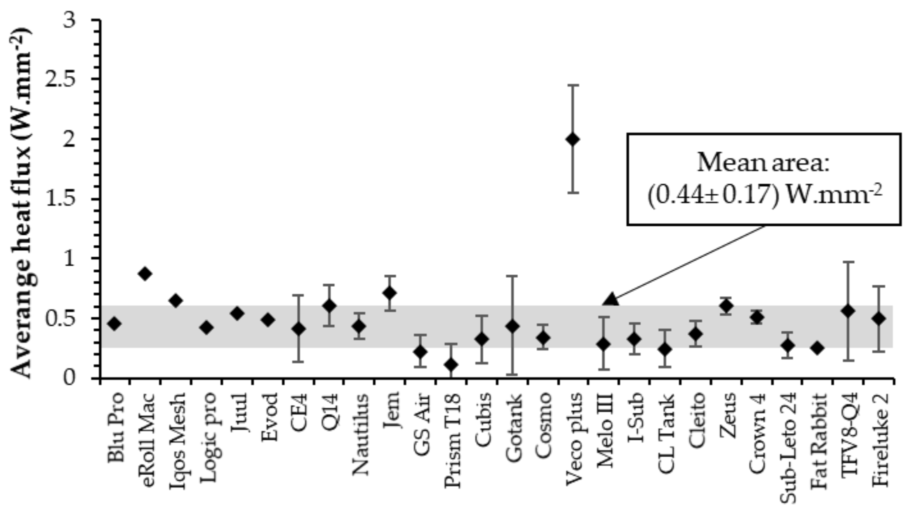

Figure 11. Average heat flux of the twenty-six tested devices.

Except for the Veco plus, the average heat flux presents an interesting dispersion that is around (0.44 ± 0.17) W mm^{-2}. This might represents a pleasant limit of the generated aerosol. Veco plus is a device with a notable element of design that is not present in the others: its wire is melded into a ceramic element. Its complete immersion might allow a higher heat flux comparing with partially immerged wire.

3.4. Air Resistance

Figure 12 illustrates the pressure drop measured according to the airflow rate applied. The respiratory limit induced by the lungs is added as a red line. The calibration curve is also added as a green line.

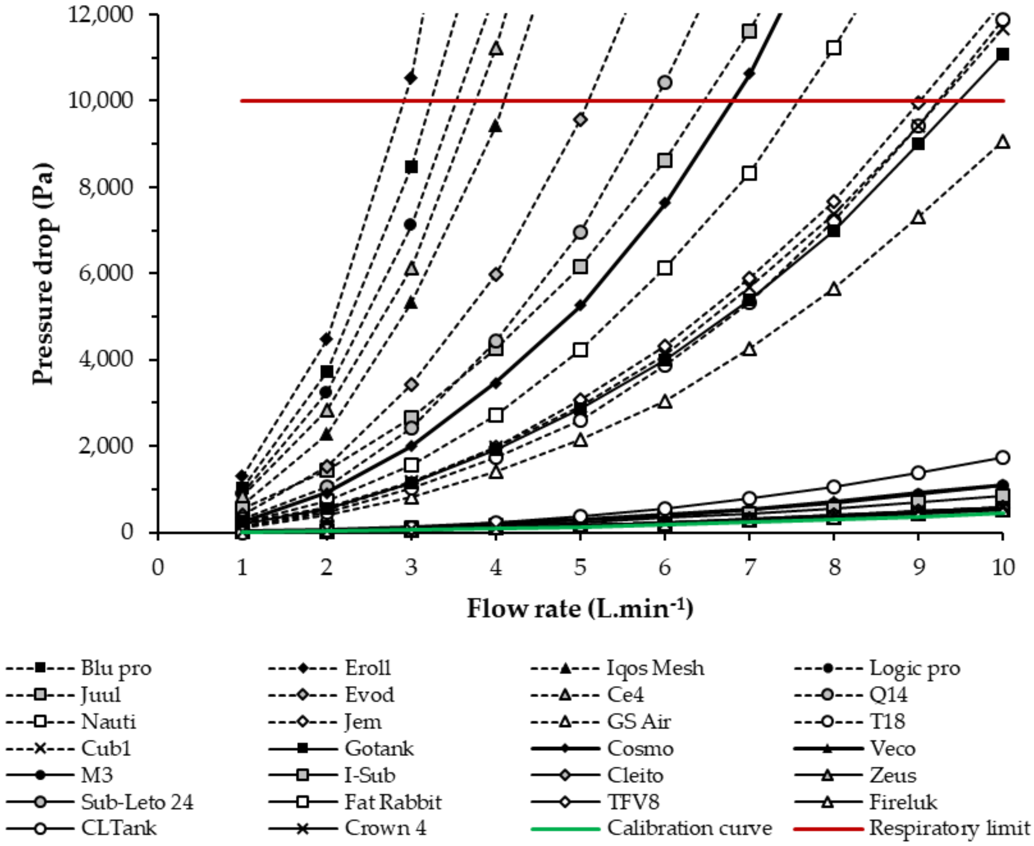

Figure 12. Pressure drop curves of the twenty-six tested devices according to the airflow rate.

Graphically, each device has a parabolic profile due to the pressure drop square root (Equation (3)), then verified with the R-square (0.9904–0.9996) when air resistances are extracted. Two groups are clearly identifiable. The first one reaches the respiratory limit for airflow rate between 2 and 11 L min^{-1} and curves are dispersed. The second group have low-pressure drops and do not exceed 2000 Pa at 10 L min^{-1} with a small variability. Their curves look to be overlapped and are hardly separately observable. Finally, the air resistances are determined. They are subtracted by the empty setup air resistance (obtained by the calibration). Figure 13 illustrated the treated air resistance.

The air resistance values have a wide range of values (between 0.15 and 33 Pa$^{0.5}$ min L^{-1}). Therefore, eleven values are below 2.5 Pa$^{0.5}$ min L^{-1} with one value upper than 1.2 Pa$^{0.5}$ min L^{-1}.and seven values below 0.3 Pa$^{0.5}$ min L^{-1}. In the other side, fifteen values are upper than 7 Pa$^{0.5}$ min L^{-1} with five values upper than 25 Pa$^{0.5}$ min L^{-1}, five between 11 and 18 Pa$^{0.5}$ min L^{-1} and five between 7 and 9 Pa$^{0.5}$ min L^{-1}. The two groups are clearly observable and an air resistance of 4.8 Pa$^{0.5}$ min L^{-1} could be used as a limit between them.

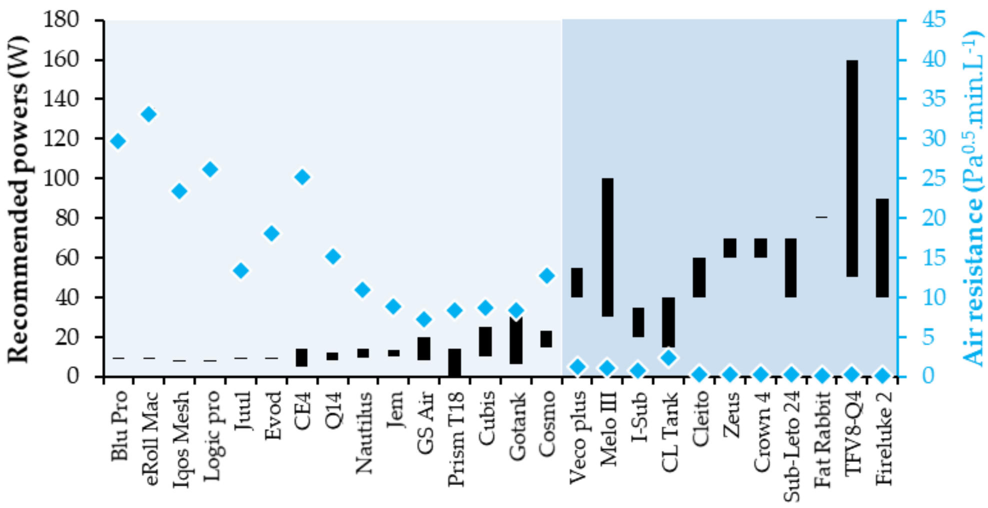

Figure 13. Recommended powers of the twenty-six tested devices regarding their air resistances (extracted from the pressured drop measurements).

4. Discussion

Through this publication, we develop a classification based on mechanical characteristics: recommended powers, electrical resistance, wire surface and air resistance of an atomiser. We explain how these two groups of devices are linked to the inhalation behaviours. In reality, this illustrates how manufacturers probably developed devices: regarding the inhalation behaviour. Therefore, this new classification is not based on "what this device looks like?" but for "who these devices are intended for?".

Additionally, results show that inhaling with a DL behaviour through a device with a high air resistance (first group) is physically impossible. In the other side, a user has to restrict significantly his inhalation in order to practice MTL with atomisers having low air resistance (second group). This would lead to discomfort during vaping. This also illustrates how the respiratory limits influence the design of the devices. Furthermore, we highlight an average heat flux (0.43 ± 0.17 W mm^{-2}) that looks to be a constant of devices (excepted for Veco plus). In a recent publication [4], authors carried boiling experiments using wire immersed in propylene-glycol and glycerol. They found a critical heat flux of 0.34 W mm^{-2} for PG and 0.87 W mm^{-2} for VG. These fluxes are consistent with the average one observed through the devices. These fluxes also appear to be a boiling regimen limit between a low and a high aldehyde production regimen. Consequently, the power ranges look to be empirically required in a range reducing the risk for the consumers.

Therefore, we illustrate the link between the inhalation behaviour and the mechanical characteristics of the device. By coupling these observations and our previously published ones [5], we highlight the needed to use a vaping regimen adapted to the group of devices tested. Otherwise, results would not be consistent with the real condition of use. Without considering this link, this is the functioning itself of a device that is impaired. Carrying this kind of experiments would mainly provide conclusions showing a malfunctioning (low energy efficiency, short power range in optimal regimen of vaporization) while in reality, they reflect a misuse.

To avoid this, we propose considering the defined limits between the two groups as criteria to select the vaping regimen that should be applied. By default, a device is considered as a one of the first group. Then, if a device has one characteristic of the second one (commonly called sub-ohm), even air resistance, it should be used with a direct lung vaping regimen like the one previously proposed. Finally, Figure 14 summarizes the classification developed in this publication and provides a graphical illustration of the discussions.

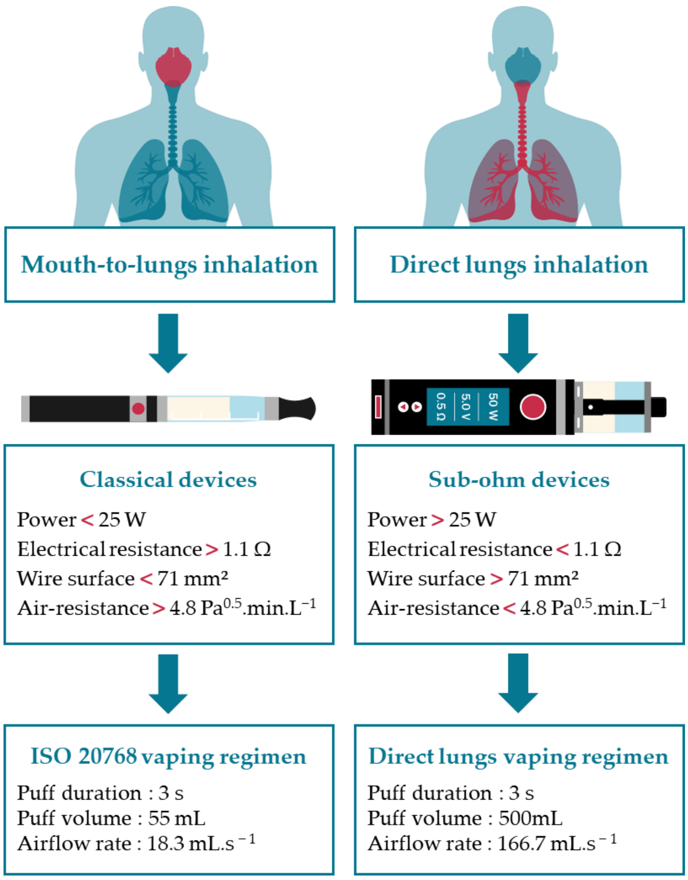

Figure 14. Proposed classification based on mechanical characteristics and advise for vaping regimens selection in the emission generation of electronic cigarette.

5. Conclusions

The aim of this publication was to provide a more technical classification of electronic cigarettes. To do so, twenty-six devices were disassembled. Each heating element has non-resistive brackets welded to a resistive part that heats. Four types of resistive parts were observed: a simple wire, two parallel wires, one or two wires with a rolled around non-resistive wire, and a small wire structured in mesh. Except for the Iqos mesh that is too thin to be correctly measured, all the surfaces of the resistive part were calculated using the length and the diameter. Then, the air resistance of each device was determined using pressure drop measurements. Through these experiments, recommended powers, electric resistance, wire surface, and air resistance show two main groups of devices (commonly named classical and sub-ohm electronic cigarettes) designed for two inhalation behaviours: mouth-to-lungs and direct lungs. These groups are limited by a required power of 25 W, an electrical resistance of 1.1 Ω, a wire surface of 71 mm^2, and an air resistance of 4.8 $Pa^{0.5}$ min L^{-1}. Some devices were just between the two groups. The analysis of more devices would allow a better determination of these limits. However, they could be used as requirements for direct lung vaping regimen use.

Through this publication, we exposed necessary elements to grasp the functioning of an electronic cigarette. As explained in the introduction, electronic cigarettes are heat exchangers. The energy delivered is diffused to the air and to the e-liquid. We described the different designs of heating elements available in the devices. With the surface determination, we concluded that a specific heat flux seems to be a constant in most of the devices, and we provided a range of value calculated. This provides an important comprehension of how an e-liquid is heated. Additionally, the air resistance was extracted from pressure drop measurements. These values need puffing topography in order to determine if users inhale at an airflow corresponding to an average constant pressure drop. However, air resistance allows the determination of a characteristic speed of air needed in the calculation of heat exchange coefficient. Future studies will be focused on the thermal behaviour of an e-cig using this technical information.

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References

1. ANSES; Déclarations Des Produits Du Tabac et Produits Connexes En France—Produits Du Vapotage—Bilan 2016–2020. Available online: https://www.anses.fr/fr/system/files/CONSO2018SA0189Ra-2.pdf (accessed on 2 February 2021).
2. Williams, M.; Talbot, P. Design Features in Multiple Generations of Electronic Cigarette Atomizers. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2904. [CrossRef] [PubMed]
3. Soulet, S.; Duquesne, M.; Toutain, J.; Pairaud, C.; Lalo, H. Influence of Coil Power Ranges on the E-Liquid Consumption in Vaping Devices. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1853. [CrossRef] [PubMed]
4. Talih, S.; Salman, R.; Karam, E.; El-Hourani, M.; El-Hage, R.; Karaoghlanian, N.; El-Hellani, A.; Saliba, N.; Shihadeh, A. Hot Wires and Film Boiling: Another Look at Carbonyl Formation in Electronic Cigarettes. *Chem. Res. Toxicol.* **2020**, *33*, 2172–2180. [CrossRef] [PubMed]
5. Soulet, S.; Duquesne, M.; Toutain, J.; Pairaud, C.; Mercury, M. Impact of Vaping Regimens on Electronic Cigarette Efficiency. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4753. [CrossRef] [PubMed]
6. ISO. *ISO/20768—Vapour Products—Routine Analytical Vaping Machine—Definitions and Standard Conditions*; 2018; p. 7. Available online: https://www.iso.org/fr/standard/69019.html (accessed on 29 January 2018).
7. Rahn, H.; Otis, A.B.; Chadwick, L.E.; Fenn, W.O. The pressure-volume diagram of the thorax and lung. *Am. J. Physiol. Content* **1946**, *146*, 161–178. [CrossRef] [PubMed]
8. Spiro, S.; Silvestri, G.; Agustí, A. *Clinical Respiratory Medicine*, 4th ed.; Elsevier: Philadelphia, PA, USA, 2012; ISBN 978-1-4557-0792-8.
9. Shah, R.K.; Sekulic, D.P. *Fundamentals of Heat Exchanger Design*; John Wiley & Sons: Hoboken, NJ, USA, 2003; ISBN 978-0-471-32171-2.
10. Kakaç, S.; Liu, H.; Pramuanjaroenkij, A. *Heat Exchangers: Selection, Rating, and Thermal Design*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2020; ISBN 978-0-429-89204-2.
11. Singh, Y. Electrical resistivity measurements: A review. *Int. J. Mod. Phys. Conf. Ser.* **2013**, *22*, 745–756. [CrossRef]
12. Kanthal®. Available online: https://www.kanthal.com/en/ (accessed on 26 September 2018).
13. Precision Tubes—Seamless and Welded | Fine Tubes. Available online: www.finetubes.co.uk/ (accessed on 11 February 2021).
14. Alloy Wire International—Manufacturers of High Performance Exotic Alloys. Available online: https://www.alloywire.com/ (accessed on 11 February 2021).
15. ASTM International. *ASTM/B258—Specification for Standard Nominal Diameters and Cross-Sectional Areas of AWG Sizes of Solid Round Wires Used as Electrical Conductors*; 2018. Available online: https://www.astm.org/Standards/B258.htm (accessed on 2 February 2021).
16. Clark, A.; Hollingworth, A. The Relationship Between Powder Inhaler Resistance and Peak Inspiratory Conditions in Healthy Volunteers—Implications for In Vitro Testing. *J. Aerosol Med.* **1993**, *6*, 99–110. [CrossRef] [PubMed]
17. Srichana, T.; Martin, G.; Marriott, C. Dry powder inhalers: The influence of device resistance and powder formulation on drug and lactose deposition in vitro. *Eur. J. Pharm. Sci.* **1998**, *7*, 73–80. [CrossRef]
18. Colard, S.; Julien, S. Characterisation of the Draw Resistance Across a Lit Cigarette. *Beitr. Zur Tab. Int. Tob. Res.* **2013**, *25*, 586–594. [CrossRef]