Comparison of carbonyls emitted from conventional cigarettes, electronic cigarettes and heated tobacco products

Niki Matsouki¹, Emmanouil Konstantinidis¹, Chara Tsipa¹ and Efthimios Zervas¹,²

¹Hellenic Open University, Patras, Greece
²zervas@eap.gr

Abstract. Conventional cigarettes, electronic cigarettes (e-cigs) and heated tobacco products (HTPs) emit a wide number of chemical substances which are inhaled by the user. An extended bibliographic analysis of the available data concerning carbonyls identity and quantity in tobacco products gas emissions was performed. Published works in Scopus and Pubmed databases from 2010 until 2020, in English language, were used in order to collect the data, using specific keywords. The number of carbonyls detected in the emissions of conventional cigarettes’ is 43 (97 articles are included), 33 in e-cigs’ (70 articles included) and 62 in HTPs’ (50 articles included). Nineteen compounds are present in emissions of all three tobacco products. Their emitted concentration is generally higher in the case of conventional cigarettes compared to the other two products, except from 5-methylfurfural and methylglyoxal that had the higher concentrations in HTPs, plus benzaldehyde and formaldehyde that had higher concentrations in e-cigs. However, HTPs has the higher number of unique carbonyls emitted.

1. Introduction

Tobacco products, especially conventional cigarettes, electronic cigarettes (e-cigs) and heated tobacco products (HTPs) include in their gas emissions several chemical substances which are inhaled by the user [1,2]. The three emissions regulated in EU are tar, nicotine and CO [3]. Several other families of compounds are emitted, such as hydrocarbons, carbonyls, nitrosamines [4-10], but also particles [11,12], or metals [13,14].

Many of these substances are known to have a negative impact on human’s health. Carbonyls is one of the families of compounds emitted from conventional cigarettes; as this family of compounds is an intermediate product of the combustion of organic compounds [15]. However, even no combustion occurs in the case of electronic cigarettes, carbonyls are also found in their emissions [16-18]. Also, carbonyls are emitted from heated tobacco products [19-20].

In order to compare the emissions of carbonyls of conventional cigarettes, electronic cigarettes and heated tobacco products, we performed an extended bibliographic search to record the type and the concentration of these compounds in emissions of the three tobacco products.

2. Methodology

Data was collected from the papers published in Scopus and Pubmed databases, in English language, and during the years 2010–2020. Three different searches were performed, one for each type of tobacco product, using specific keywords. The searches performed for conventional cigarette,
electronic cigarette and for heated tobacco products are respectively (a second search is performed in Scopus the case of heated tobacco products, because all the keywords cannot fit to the search bar):
- cigarette * AND (emission * OR vapor OR aerosol OR voc OR pollutant* OR particle* OR particulate matter" OR pm),
- (ecig OR e-cig OR "electronic cigarette*" OR e-cigarette* OR "Vape pen*" OR "Vaping device" OR "electronic nicotine delivery system") AND (emission* OR vapor OR aerosol OR voc OR pollutant* OR particle* OR "particulate matter" OR pm),
- (hnb OR "heat not burn" OR "heat-not-burn" OR "heated tobacco product*" OR glo OR plum OR iqos OR iuoc OR lil OR mok OR puzzle OR teeps) AND (emission* OR vapor OR aerosol OR voc OR pollutant* OR particle* OR "particulate matter" OR pm).
- "Tobacco heating system" AND (emission* OR vapor OR aerosol OR voc OR pollutant* OR particle* OR "particle matter" OR pm).

The search performed in pubmed is: (HNB OR "Tobacco heating system" OR "heat not burn" OR "heat-not-burn" OR "heated tobacco product*" OR glo OR plum OR IQOS OR IUOC OR Lil OR Mok OR Puzzle OR TEEPS) AND (emission* OR vapor OR aerosol OR voc OR pollutant* OR particle* OR "particulate matter" OR pm).

Duplicate papers were eliminated; also papers from the references of the initial ones were included.

Data collection focused on carbonyl emission. Three files, one for each product, were constructed. These files include information about the name of the compound, the CAS number, the chemical family (aldehyde or ketone), the concentration (average, minimum and maximum and standard deviation), the units, the emissions generation method, the gas collection method, the analytical method and also the limit of detection and limit of quantification of this analytical method (when given). The average concentration values of all the articles were calculated for the carbonyl compounds and classified according to the different units used. Then, a comparison of all carbonyl compounds emitted from the three tobacco products is performed.

3. Results
The bibliographic search, using the above keywords, resulted to 4,275 unique articles for conventional cigarette, 1,434 for e-cigs and 810 for HTPs. The number of papers dealing with carbonyls in gas emissions is 97, 70 and 50 respectively, while the number of different carbonyls detected in the tobacco products emissions is 43, 33 and 62 respectively for conventional cigarettes, e-cigs and HTPs.

These compounds are presented in alphabetical order in table 1. The first three columns present the compounds found only in the emissions of conventional cigarettes, of e-cigs or of HTPs, while the last column shows the compounds found in the emissions of all three different tobacco products.

| Compounds detected in all products gas emissions |
|-----------------------------------------------|
| Compounds detected in all products gas emissions |
| Conventional cigarettes | e-cigs | HTPs |
| 2,3-dimethyl-2-cyclopenten-1-one | 2,3-pentanedione | 1,2-Cyclohexanediene |
| 2,3-pentanedione | Benzyl-methyl-ketone | 1-Acetoxyl-2-propanone |
| 2,4-pentanedione | Decanal | 1-Chloro-2-propanone |
| 2-cyclohexen-1-one | Ethyl vanillin | 2,2,6-trimethyl-Cyclohexanone |
| 2-hexanone | Glycolaldehyde | 2,3-Dimethyl-2-cyclopenten-1-one |

Table 1. Carbonyls detected in tobacco products gas emissions.
| Chemical Compound          | Synonym                                      |
|---------------------------|----------------------------------------------|
| 2-methyl-2-butenal        | Glyoxal                                      |
| 2-methyl-2-cyclopenten-1-one | m-methylbenzaldehyde                        |
| 2-methylbutanal           | Nonanal                                      |
| 2-methyl-cyclopentanone   | 2,3-pentanedione                            |
|                           | 2,4-dimethyl-3-pentanone                    |
| 2-methylpropanal          | Vanillin                                     |
| 2-pentanone               | ß-damascon                                   |
|                           | 2-cyclopenten-1-one                         |
|                           | 2-Cyclopenten-1-one, dimethyl-              |
|                           | (configurational isomer 1)                  |
| 3-(methylthio)propanal    | 2-Cyclopenten-1-one, dimethyl-              |
|                           | (configurational isomer 2)                  |
| 3-penten-2-one            | 2-formyl-1-methylpyrrole                    |
| 6-methyl-5-hepten-2-one   | 2-heptanone                                  |
| Acetophenone              | 2-heptanone, 6-methyl-                       |
| Acetoxyacetone            | 2-Hexanone                                   |
| Farnesylacetone           | 2-methyl-2-butenal                           |
| Isoforone                 | 2-methyl-2-cyclopenten-1-one                |
| Methyl vinyl ketone       | 2-methyl-3-pentanone                         |
| Pentan-3-one              | 2-methylbutyraldehyde                       |
| Phenylacetaldehyde        | 2-methylcyclopentanone                      |
|                           | 2-nonenal                                    |
|                           | 2-pentanone                                  |
|                           | 3,4-hexanedione                              |
|                           | 3-hexanone                                   |
|                           | 3-methyl-2-butanone                          |
|                           | 3-methyl-2-butenal                           |
|                           | 4-pentenal                                   |
|                           | 6-methyl-5-hepten-2-one                      |
|                           | Benzeneacetaldehyde                          |
|                           | Cyclobutanone                                |
|                           | Decanal                                      |
Ethyl vinyl ketone  
Farnesyl acetone  
Glyoxal  
Heptanal  
Isobutyraldehyde  
Methyl vinyl ketone  
m-tolualdehyde  
Nonanal  
Pentan-3-one  
trans-2-Pentalenal  
trans-3-Penten-2-one

In order to compare the emissions of the three tobacco products, Table 2 shows the 19 compounds, and their concentrations (in the same unit, if possible) in the emissions of the three tobacco products.

**Table 2. Concentration of carbonyls detected in the emissions of all three tobacco products.**

| Compound name                  | Conventional cigarette | e-cigarette | HTPs |
|--------------------------------|------------------------|-------------|------|
|                                | Aver.      | Std dev | Unit | Aver.      | Std dev | Unit | Aver.      | Std dev | Unit |
| 3-hydroxybutan-2-one           | 0.079      |         | μg/puff | 0.020      |         | μg/12puffs | 6.866      |         | μg/item |
| 3-methylbutanal                | 133.3      | 0.38    | μg/item | 0.187      |         | μg/12puffs | 33.2       | 1.56     | μg/item |
| 4-methylpentan-2-one           | 0.2        | 0.11    | μg/item | 1.440      |         | μg/m3      | 0.2725     |         | μg/item |
| 5-methylfurfural               | 5.25       |         | μg/item | 3240.0     |         | μg/m3      | 8.765      |         | μg/item |
| Acetaldehyde                   | 1034.64    | 123.1   | μg/item | 23.938     | 12.694  | μg/12puffs | 265.07     | 26.4659  | μg/item |
| Acetone                        | 413.35     | 30.7    | μg/item | 12.468     | 6.667   | μg/12puffs | 57.281     | 7.8729   | μg/item |
| Acrolein                       | 123.784    | 13.1    | μg/item | 14.848     | 5.398   | μg/12puffs | 15.093     | 2.2655   | μg/item |
| Benzaldehyde                   | 23.65      | 0.04    | μg/item | 32.008     |         | μg/12puffs | 1.0433     | 0.75     | μg/item |
| Butanal                        | 48.1       | 3.7     | μg/item | 0.092      | 0.089   | μg/12puffs | 19.384     | 1.6606   | μg/item |
| Crotonaldehyde                 | 39.40      | 4.4     | μg/item | 0.082      | 0.072   | μg/12puffs | 6.6119     | 1.279    | μg/item |
| Formaldehyde                   | 69.080     | 15.287  | μg/item | 94.729     | 36.222  | μg/12puffs | 10.659     | 1.8873   | μg/item |
| Furfural                       | 38.3       |         | μg/item | 31.200     |         | μg/12puffs | 31.4       | 0.23     | μg/item |
| Hexanal                        | 71.000     |         | μg/item | 16.080     |         | μg/m3      | 0.9        | 0.14     | μg/item |
| Hydroxyacetone                 | 12.400     |         | μg/item | 18.000     |         | μg/12puffs | 86.85      |         | μg/item |
| Methylacrolein                 | 67.192     | 5.10    | μg/item | 2.587      |         | μg/L        | 11.266     | 0.305    | μg/item |
| Methyl ethyl ketone            | 103.102    | 10.220  | μg/item | 0.830      |         | μg/12puffs | 17.239     | 2.4347   | μg/item |
| Methylglyoxal                  | 18.200     | 0.678   | μg/item | 0.552      | 1.225   | μg/12puffs | 28.005     | 1.465    | μg/item |
| Pentanal                       | 46.000     |         | μg/item | 0.096      |         | μg/12puffs | 10.209     | 1.48     | μg/item |
| Propanal                       | 86.95      | 10.942  | μg/item | 0.820      | 0.600   | μg/12puffs | 21.390     | 2.90     | μg/item |

Table 3 presents the concentrations of the rest of carbonyls, those detected in the emissions of one or two tobacco products. The concentration is shown as an average, or as the range minimum-maximum value when the average value was not recorded in the source articles. For the electronic cigarettes, the values per puff were multiplied by 12, considering that 12 puffs equal to one cigarette. For uniformity reasons, other conversions in the units of the original values were made and include μg/10puffs, μg/9puffs or μg/200puffs to μg/puff, by dividing by 10, 9, or 200, μg/ml to μg/L, ng/L to μg/L and mg/cigarette or ng/cigarette to μg/cigarette. In the case of only
minimum and maximum concentrations calculated and not an average, the maximum value is the one presented in the table. The concentration of fourteen compounds in the gaseous emissions of tobacco products are presented using the same unit (μg/cig or μg/item and μg/12puffs), although the method for generating these emission and the analytical method used may differ significantly.

Table 3: Concentration of carbonyls detected in the emissions of one or two tobacco products.

| Compound name                      | Aver. or min-max | Stdev | Unit | Compound name                             | Aver. or min-max | Stdev | Unit |
|------------------------------------|------------------|-------|------|-------------------------------------------|------------------|-------|------|
| 2,3-butanedione                    | 236.187          | 25.68 | μg/item | 1,2-Cyclohexanone                        | 0.083            |       | μg/item |
| 2,3-dimethyl-2-cyclopenten-1-one   | 1.260-1.830      | 0.100-0.070 | μg/item | 1-Acetoxy-2-propanone                    | 14.55            |       | μg/item |
| 2,3-pentanediode                   | 36.374           | 4.908 | μg/item | 1-Chloro-2-propanone                     | 0.546            |       | μg/item |
| 2,4-pentanediode                   | 17.933-67.733    | 2.000-6.733 | μg/item | 2,2,6-trimethyl-Cyclohexanone             | 0.1              | 0.01 | μg/item |
| 2,5-dimethylbenzaldehyde           | 4.54             | 0.84  | μg/m3  | 2,3-Dimethyl-2-cyclopenten-1-one         | 1.05             |       | μg/item |
| 2-cyclohexen-1-one                 | 0.490-2.420      | 0.010-0.070 | μg/item | 2,3-pentanediode                         | 6.283            | 0.745 | μg/item |
| 2-hexanone                         | 0.2              | 0.08  | μg/item | 2,4-dimethyl-3-pentanone                 | 0.5              |       | μg/item |
| 2-methyl-2-butenal                 | 1.000            | 0.6   | μg/item | 2,4-Pentanediode                         | 0.1              | 0.000 | μg/item |
| 2-methyl-2-cyclopenten-1-one       | 3.220-4.250      | 0.150-0.110 | μg/item | 2-cyclohexen-1-one                       | 0.436            |       | μg/item |
| 2-methylbutanal                    | 179.000          |       |       | 2-cyclopenten-1-one                      | 4.3              |       | μg/item |
| 2-methyl-cyclopentanone            | 0.9              | 0.1   | μg/item | 2-Cyclopenten-1-one, dimethyl- (configurational isomer 1) | 0.273 |       | μg/item |
| 2-methylpropanal                   | 58.64            | 2.02  | μg/item | 2-Cyclopenten-1-one, dimethyl- (configurational isomer 2) | 0.135 |       | μg/item |
| 2-pentanone                        | 12.32            | 1.316 | μg/item | 2-formyl-1-methylpyrrole                 | 0.128            |       | μg/item |
| 3-(methylthio)propanal             | 1.1              | 0.16  | μg/item | 2-heptanone                              | 0.229            |       | μg/item |
| 3-pentan-2-one                     | 0.410-1.180      | 0.080-0.210 | μg/item | 2-heptanone, 6-methyl-                   | 0.2383           | 0.00  | μg/item |
| 4-methylbenzaldehyde               | 0.157            |       | μg/puff | 2-Hexanone                               | 0.1              | 0.01  | μg/item |
| 6-methyl-5-hepten-2-one            | 0.210-0.290      | 0.02  | μg/item | 2-methyl-2-butenal                       | 1.49             |       | μg/item |
| Acetophenone                       | 0.370-0.560      | 0.030-0.010 | μg/item | 2-methyl-2-cyclopenten-1-one             | 2.34             |       | μg/item |
| Acetoxyacetone                     | 9.23             |       | μg/item | 2-methyl-3-pentanone                     | 0.189            |       | μg/item |
| Chemical Name                  | Concentration | Unit         | Source                        |
|-------------------------------|---------------|--------------|-------------------------------|
| Farnesyl acetone             | 8.815         | μg/item      | 2-methylbutyraldehyde         |
| Isoforone                    | 0.080-0.110   | μg/item      | 2-methylcyclopentanone        |
| Methyl vinyl ketone          | 51.245-77.250 | μg/item      | 2-nonanal                     |
| Pentan-3-one                 | 5.43          | μg/item      | 2-pentanone                   |
| Phenylacetaldehyde           | 0.900-2.190   | μg/item      | 3,4-hexanedione               |
| e-cigarettes                 |               |              |                               |
| 2,3-butanedione              | 0.5340        | μg/puff      | 3-hexanone                   |
| 2,3-pentanedione             | 0.0005        | μg/puff      | 3-methyl-2-butanone           |
| 2,5-dimethylbenzaldehyde     | 4.5400        | μg/m3        | 4-pentenal                    |
| 4-methylbenzaldehyde         | 0.0461        | μg/L         | 6-methyl-5-hepten-2-one       |
| Benzyl-methyl-ketone         | 0.0100        | mg/g e-liquid| Benzeneacetaldehyde           |
| Decanal                      | 1.800         | μg/m3        | Cyclobutanone                 |
| Ethyl vanillin               | 0.8300        | mg/g e-liquid| Decanal                       |
| Glycolaldehyde               | 0.0048-0.0279 | mg/g e-liquid| Ethyl vinyl ketone            |
| Glyoxal                      | 0.0563        | μg/puff      | Farnesyl acetone              |
| m-methylbenzaldehyde         | 0.0026-0.0063 | mg/puff      | Glyoxal                       |
| Nonanal                      | 9.100         | μg/m3        | Heptanal                      |
| o-methylbenzaldehyde         | 0.0007-0.0071 | μg/puff      | Isobutylaldehyde              |
| Vanillin                     | 0.9130-1.4730 | mg/g e-liquid| m-tolualdehyde                |
| β-damascon                   | 250.00        | μg/m3        | Nonanal                       |

4. Discussion

Totally, 83 different compounds were found in the literature. The number of compounds detected in the emissions of all three products is only 19. HTPs were found to produce the highest number of compounds (62), followed by conventional cigarettes (43) and e-cigs (33). However, conventional cigarettes produce, in general, higher concentration of carbonyls than the other two products. More specifically, only benzaldehyde and formaldehyde were detected in higher concentrations in e-cigs emissions compared to conventional cigarettes. Literature suggests that high amounts of carbonyls are produced by e-cigs under high voltage vaping conditions [21-22]. The comparison of the same 14 compounds emitted from HTPs and conventional cigarettes shows higher concentrations of
hydroxyacetone and methylglyoxal from HTPs. For e-cigs and HTPs there is not a specific trend, though concentration in HTPs emissions was generally higher than in e-cigs.

It should be mentioned that the emission of carbonyls observed in the published articles are found within a wide range. The methods used for smoke generation, collection and analysis of carbonyls are very different and this is another parameter influencing this range.

5. Conclusions
According to the published works, a high number of carbonyls is detected in the mainstream smoke of tobacco products, both conventional cigarettes and novel tobacco products (e-cigs and HTPs). Conventional cigarettes emit the higher concentrations of carbonyls; however, HTPs produce the highest number of these compounds. The range of emissions is quite high; the different methods used in the literature for the generation mainstream smoke, the collection and analysis of carbonyls are very different and this is another parameter influencing this range.

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