Temperature influences on the performance of biodiesel phononic crystal sensor

Abd Allah Shehatah and Ahmed Mehaney
Physics Department, Faculty of Science, Beni-Suef University, Beni-Suef, 62514, Egypt
E-mail: ahmed011236@science.bsu.edu.eg

Keywords: phononic crystals, biodiesel, sensor, band gap, reflection spectrum, acoustic wave

Abstract
In the present work, a 1D phononic crystal model is introduced as a biodiesel sensor. The proposed sensor can sense and distinguish between different biodiesel fuels with high performance. The sensor structured from a defect layer filled with biodiesel in the middle of a 1D binary structure as the configuration [Al/epoxy)biodiesel(Al/epoxy)]. Using the transfer matrix method, the reflection spectrum of the biodiesel sensor is calculated. The influences of different biodiesel fuels on the resonant peaks are compared and discussed. Also, different temperatures in the range from 20 °C to 50 °C were considered to show the sensor performance under temperature effects. Based on our results, the presented sensor can be considered as a selective sensor between different biodiesel fuels (e.g. Methyl Soy Ester, Oxidized Soy Ester, Ethyl Soy Ester, Certified D-2 and Methyl Laurate) and more sensitive to their temperature changes. For example, at temperature 30 °C the sensitivity and quality factor of the sensor reached the values of about 265 Hz °C⁻¹ and 55.12 for Methyl Soy Ester, 261.5 Hz °C⁻¹ and 55.8 for Oxidized Soy Ester, 260.9 Hz °C⁻¹ and 56.2 for Ethyl Soy Ester, 291.7 Hz °C⁻¹ and 58.3 for Certified D-2, 361.6 Hz °C⁻¹ and 56.3 for Methyl Laurate, respectively.

1. Introduction
Phononic crystals (PnCs) are artificial composites can inhibit the propagation of mechanical waves at certain frequencies known as phononic band gaps [1–6]. Within which elastic and acoustic waves are fully suppressed. PnCs constructed by a periodic arrangement of two or more materials in 1D, 2D or 3D structures [7–11]. In recent years, many interesting applications based on these materials have introduced such as filters, multiplexing systems, heat isolation devices, energy harvesting structures, waveguides, etc [12–22]. One of the fundamental applications of PnCs is the possibility of achieving acoustic sensors [7, 23]. A H Aly et al introduced theoretically the idea of using 1D defective PnC as a sensor design based on the intensity of the transmitted (resonant) modes [6]. Where the type of unknown liquid can be specified by the transmission intensity of the resonant mode. A 1D multi-layered PnC sensor structure was introduced experimentally by S Villa-Arango et al [20]. G Sharma et al designed theoretically a Si–SiO₂ phonic crystal for simultaneous sensing of liquids by electromagnetic and mechanical waves. They investigated using the transfer matrix method the possibility of sensing biodiesel in a binary mixture of diesel and biodiesel [24]. Also, a 1D PnC structure works as a biodiesel sensor has been presented theoretically by A Mehaney [25]. This biodiesel sensor has drawbacks such as large size (5 cm) and its inability to recognize the type of the biodiesel fuel. Moreover, R Lucklum et al introduced a different type of PnC sensors in the form of a sandwiched PnC between two stacked layers on the top of surface acoustic wave device [26]. Based on the previous success of PnCs in the field of biosensors. PnC sensors must play a bigger role in detecting and measuring biofuels physical properties due to its important applications. Biodiesel has many benefits like renewable, non-toxic and biodegradable [27–34]. Therefore, a PnC sensor platform must be applied for recognizing and measuring the physical properties of the different biodiesel fuels.

In this paper, we study theoretically the effects of temperature changes on the performance of biodiesel PnC sensor. A 1D binary PnC model can distinguish between different biodiesel fuels under temperature considerations. Different biodiesel fuels such as Methyl Soy Ester, Oxidized Soy Ester, Ethyl Soy Ester, Certified
D-2 and Methyl Laurate in a defect layer of the PnC are considered. The effects of these fuels on the resonant peaks will be studied and compared. The quality factor and sensitivity of the sensor will be calculated and tabulated for all fuels at different temperatures.

2. Theoretical analysis and method of calculations

Depending on the transfer matrix method (TMM) we study the acoustic waves interactions with the PnC structure [35, 36]. Assume a 1D binary PnC constructed from \( n \) unit cells as shown in figure 1. Each unit cell has two different layers from aluminum and epoxy signified by the symbols (X, Y), where the lattice constant is \( a = a_1 + a_2 \).

The acoustic wave motion through the 1D PnC structure can be written in the following equation:

\[ \rho \ddot{u} = \sigma_x + f, \]

where \( \rho = \rho(x), u = u(x, t), \sigma = \sigma(x, t), f = f(x, t) \) and \( x \) denote the density, displacement, stress, external force and the position coordinates, respectively.

The equation of motion will be recast to a dimensionless form by introducing the following dimensionless local coordinates:

\[ \xi_j = X_j/\bar{a}_j, \]

where \( \bar{a}_j \) is the thickness mean value of material A \( (j=1) \). The general harmonic dimensionless solution for equation (1) will be as follow:

\[ \varphi(\xi_j, \eta_j, t) = [A_1 \exp(-i\xi_j \zeta_j) + A_2 \exp(i\xi_j \zeta_j)] \exp(-i\omega t), \]

where \( 0 \leq \xi_j \leq \xi_j = a_j/\bar{a}_j, i^2 = -1, q_{1j} = \sqrt{(\omega \bar{a}_j/\sigma_{1j}) - k_j^2}, \zeta_j \) are the dimensionless thickness of each layer, \( \omega \) is the angular frequency, \( \sigma_{1j} \) is the longitudinal acoustic wave velocity and \( A_1, A_2 \) are unknown coefficients to be determined. After conducting a lot of mathematical calculations that can be found in [35, 36] the relation between these two state vectors is given in the following form

\[ V^{(k)}_{(j)} = T_j^{T} V^{(k)}_{(j)}, \]

where \( T_j \) are 2 \( \times \) 2 transfer matrix. The reflection coefficient of an acoustic wave propagates normally in the \( x \)-direction through a PnC composed of \( N \) layers and bonded between two semi-infinite materials can be written as follow:

\[ \frac{U_i}{U_0} = \frac{T_{12} + E_0 - E_0 E_x T_{21} - E_x T_{22}}{E_0(T_{11} - E_x T_{21}) - (T_{21} - E_x T_{22})}, \]

where \( U_i, U_0 \) are the reflected and incident displacement, \( T_{ij} = T(i, j) \) are the elements of the total transfer matrix method; \( T = T_{00} T_{01} \ldots T_{i} \ldots T_{1} \) with \( T'_{ik} = T_{ik} T_{ik} \)

3. Results and discussions

3.1. The reflection spectrum of the PnC structure

In the beginning, we will calculate the reflection spectrum of a perfect PnC structure. The PnC structure consists of two repeated unit cells, each unit cell consists of Al and epoxy as the configuration (Al/epoxy)\(^2\). The thickness of each layer is proposed to be \( a_1 = 3 \times 10^{-3} \) m and \( a_2 = 1 \times 10^{-3} \) m. The acoustic properties (density and speed of sound) of Al and epoxy are listed in table 1. In what follows, we will calculate the reflection spectra of the defective PnC for the different biodiesel fuels at different temperatures.
In Figure 2, the reflection spectrum of the incident acoustic wave is plotted as a function of the non-dimensional frequency \( \omega a / 2\pi c_L \). Where \( \omega \) is the angular frequency of the incident acoustic wave and \( c_L \) is the speed of sound in epoxy. As shown in Figure 2, the perfect PnC has a wide phononic band gap in the normalized frequency range 0.3 \(-\) 1.5. Such band gap will be the effective region where the localized modes will be generated. Various experimental models similar to our design were introduced in many literatures [25, 37, 38]. Therefore, the proposed sensor design can be applied and fabricated easily.

3.2. Sensor design

The proposed design of the biodiesel PnC sensor is shown in Figure 3. The sensor structure is the perfect PnC with a defect layer with a thickness \( a_d = 1.5 \times 10^{-3} \text{ m} \) in between as the configuration [(Al/epoxy)defect(Al/epoxy)]. We consider the defect layer is filled with different biodiesel fuels. Inserting a defect layer inside the perfect PnC results in generating resonant peaks, each peak frequency represents the type of the biodiesel fuel. Firstly, water was taken as a reference or standard material for all measurements.

Secondly, the defect layer is filled with different biodiesel fuels, e.g. Methyl Soy Ester, Oxidized Soy Ester, Ethyl Soy Ester, Certified D-2 and Methyl Laurate, respectively. The acoustic properties of these fuels can be found in [30].

As shown in Figure 4, the biodiesel fuels restore the incident acoustic energy and excite a transmitted resonant peak inside the phononic band gap. Each peak is related directly to the acoustic properties of each fuel. The resonant peak frequencies of Methyl Soy Ester, Oxidized Soy Ester, Ethyl Soy Ester, Certified D-2 and

| Materials     | Mass density \( \rho \times 10^3 \) (kg m\(^{-3}\)) | Speed of sound (C) \( \text{m s}^{-1} \) |
|---------------|-------------------------------------------------|------------------------------------------|
| Aluminum      | 2.7                                             | 6300                                     |
| Epoxy         | 1.18                                            | 1640                                     |
| Water         | 0.998                                           | 1483                                     |

![Figure 2. The reflection spectrum of a perfect PnC structure (Aluminum/Epoxy).](image1)

![Figure 3. A schematic diagram of the defective biodiesel PnC sensor structure.](image2)

![Table 1. Density and sound speed of materials.](image3)
Methyl Laurate are 183 090.18 Hz, 183 009.26 Hz, 182 788.14 Hz, 180 570.95 Hz and 179 617.46 Hz, respectively. Also, it is observed that as the sound speed decreases, the resonant peaks shift towards lower frequencies. Therefore, the presented sensor can produce a specific resonant peak for any biodiesel oil at specified frequency value.

3.3. Analysis of sensor performance.

The sensitivity of sensors can be calculated according to the following relation [39, 40]:

\[ s = \frac{\nabla f}{\nabla x} \]

(6)

where \( \nabla f = f_r - f_w \) is the resonant frequency shift, \( f_r \) and \( f_w \) is the resonant peak frequency of each biodiesel oil and water, respectively. \( \nabla x \) is the change of the input parameter to be measured (sound speed or temperature).

Also, the quality factor (Q-factor) can be calculated by the following relation [39, 40]:

\[ Q = \frac{f_r}{\text{FWHM}} \]

(7)

where, FWHM is the full width at half maximum of the resonant peak.

The normalized frequency, resonant peak frequency, sensitivity and Q-factor are listed in table 2 for each biodiesel oil at 20 °C. For selectivity measurements, \( \nabla x \) is considered as the change in the sound speed of each fuel.

From table 2, we can see that as the sound speed decreases, the sensitivity value increases. Also, the Q-value is almost constant for the five oils due to the constancy of the FWHM value of each oil.

3.4. Temperature effects on the reflection spectrum and sensor performance

In this part, we pay more attention to studying the effects of temperature on the reflection spectrum and on the resonant peak of each biodiesel oil. Such study will be applied to the performance analysis of the defective PnC sensor as well. In figures 5–9 different temperatures are considered on the [(Al/epoxy)/Methyl Soy Ester/(Al/epoxy)] and [(Al/epoxy)/Methyl Laurate/(Al/epoxy)], respectively (at room temperature).

Table 2. The resonant peak frequency, sensitivity and Q-factor values of the defected PnC for different biodiesel fuel at 20 °C.

| Oil            | Normalized frequency | Frequency (Hz) | Sensitivity (m\(^{-1}\)) | Q-factor |
|----------------|----------------------|----------------|--------------------------|----------|
| Methyl Soy Ester | 0.631 345            | 183 090.18     | 34.14                    | 55.1     |
| Oxidized Soy Ester | 0.631 066            | 183 009.26     | 35.39                    | 54.7     |
| Ethyl Soy Ester | 0.630 3039           | 182 788.14     | 36.02                    | 55.3     |
| Certified D-2   | 0.622 658            | 180 570.95     | 43.88                    | 57.8     |
| Methyl Laurate  | 0.619 3705           | 179 617.46     | 50.37                    | 55.7     |
Figure 5. The reflection spectra of the PhC sensor structure [(Al/epoxy)/Methyl Soy Ester/[(Al/epoxy)] at different temperatures.

Figure 6. The reflection spectra of the PhC sensor structure [(Al/epoxy)/Oxidized Soy Ester/[(Al/epoxy)] at different temperatures.

Figure 7. The reflection spectra of the PhC sensor structure [(Al/epoxy)/Ethyl Soy Ester/[(Al/epoxy)] at different temperatures.
As shown in these figures, the resonant peak position for each oil shifts towards lower frequencies with increasing temperatures. The resonant peak broadening and displacement are related directly to the sound speed and density value each oil.

The normalized frequency, frequency, sensitivity and Q-factor values for each oil at different temperatures are listed in tables 3 and 4. The temperature value of 20 °C was taken as the reference value for measurements. As seen in table 4, the temperature has a great effect on the performance parameters of the biodiesel sensor for all

Table 3. The normalized and the resonant frequencies of Methyl Soy Ester, Oxidized Soy Ester, Ethyl Soy Ester, Certified D-2 and Methyl Laurate defective PnC sensors at different temperatures, respectively.

| Temp. (°C) | MSE | OSE | ESE | CD-2 | ML | MSE | OSE | ESE | CD-2 | ML |
|-----------|-----|-----|-----|------|----|-----|-----|-----|------|----|
| 20        | —   | —   | —   | —    | —  | 55.17| 54.7 | 55.3 | 57.8  | 55.8|
| 30        | 265 | 261.5| 260.9| 291.7| 361.6| 55.12| 55.8 | 56.2 | 58.3  | 56.3|
| 40        | 271 | 265.7| 269.8| 302.5| 345.99| 56.1 | 56.2 | 56.6 | 58.8  | 57.6|
| 50        | 263 | 262.5| 265.4| 287  | 326.38| 56.6 | 56.8 | 56.7 | 59.9  | 58.3|

As shown in these figures, the resonant peak position for each oil shifts towards lower frequencies with increasing temperatures. The resonant peak broadening and displacement are related directly to the sound speed and density value each oil.

The normalized frequency, frequency, sensitivity and Q-factor values for each oil at different temperatures are listed in tables 3 and 4. The temperature value of 20 °C was taken as the reference value for measurements. As seen in table 4, the temperature has a great effect on the performance parameters of the biodiesel sensor for all
Table 4. The Sensitivity and Q-factor values of the defective PnC sensor for Methyl Soy Ester, Oxidized Soy Ester, Ethyl Soy Ester, Certified D-2 and Methyl Laurate oils at different temperatures.

| Temp (°C) | Normalized frequency | Frequency (Hz) |
|----------|----------------------|----------------|
|          | MSE                  | OSE            | ESE            | CD-2      | ML       | MSE      | OSE      | ESE          | CD-2 | ML       |
| 20       | 0.631 345            | 0.631 066      | 0.630 304      | 0.622 658  | 0.619 370 | 183 090.2 | 183 009.3 | 182 788.1 | 180 570.9 | 179 617.4 |
| 30       | 0.622 204            | 0.622 050      | 0.621 305      | 0.612 601  | 0.606 903 | 180 439.2 | 180 394.7 | 180 178.6 | 177 654.3 | 176 001.8 |
| 40       | 0.612 613            | 0.612 738      | 0.611 700      | 0.601 796  | 0.595 509 | 177 657.7 | 177 694.2 | 177 393.1 | 174 521.1 | 172 697.7 |
| 50       | 0.604 057            | 0.603 906      | 0.602 851      | 0.592 946  | 0.585 606 | 175 176.8 | 175 132.9 | 174 826.9 | 171 954.4 | 169 825.9 |
oils. For example, the sensitivity increases to the value 265 Hz °C⁻¹ with increasing the temperature from 20 °C to 30 °C for the Methyl Soy Ester. This means that each 1 °C causes the resonant peak to move about 26.5 Hz which is considered a high value for temperature effects on the biodiesel sensor and better than other previous liquid sensors [37, 38]. Also, the sensor has high Q-factor values for all oils and each value increases with increasing temperatures. Thus, we can conclude that the proposed biodiesel sensor besides its selective property between the different biofuels, it is also very sensitive to biodiesel temperature changes.

4. Conclusions

In conclusion, we studied the performance of a 1D defective PnC biodiesel sensor under temperature effects in this paper. The proposed model sensor can be considered as selective and temperature-sensitive for different biodiesel fuels e.g. Methyl Soy Ester, Oxidized Soy Ester, Ethyl Soy Ester, Certified D-2 and Methyl Laurate. Also, the resonant frequency of each fuel is plotted and analyzed at temperature changes. Moreover, the sensor showed high sensitivity and quality factor for all fuels. For example, at temperature 30 °C the sensitivity and quality factor of the sensor reached the values of about 265 Hz °C⁻¹ and 55.12 for Methyl Soy Ester, 261.5 Hz °C⁻¹ and 58.3 for Oxidized Soy Ester, 260.9 Hz °C⁻¹ and 56.2 for Ethyl Soy Ester, 291.7 Hz °C⁻¹ and 58.3 for Certified D-2, 361.6 Hz °C⁻¹ and 56.3 for Methyl Laurate, respectively. Finally, the proposed sensor has many advantages such as low cost, ease of fabrication, applicable materials and absence of any electronic components, so it can work under tough measurement conditions.

ORCID iDs

Ahmed Mehaney © https://orcid.org/0000-0002-9318-7358

References

[1] Khelifi A, Deymier P A, Rouhani B D, Vasseur J O and Dobrzynski L 2003 Two-dimensional phononic crystal with tunable narrow pass band: application to a waveguide with selective frequency J. Appl. Phys. 94 13108
[2] Mehaney A 2019 Phononic crystal as a neutron detector Ultrasound 93 37–42
[3] El-Kady I, Olsson R H and Fleming J I 2008 Phononic band-gap crystals for radio frequency communications Appl. Phys. Lett. 92 233504
[4] Sun Y, Yu Y, Zuo Y, Qiu L, Dong M, Ye J and Yang J 2019 Band gap and experimental study in phononic crystals with super-cell structure Results in Physics 13 102200
[5] Maldovan M and Thomas E L 2008 Periodic materials and interference lithography: for photonics Phononics and Mechanics 1st edn (Germany: Wiley-VCH Verlag - Weinheim)
[6] Aly A H and Mehaney A 2017 Phononic crystals with one-dimensional defect as sensor materials Indian J. Phys. 91 1021–8
[7] Lucklum R 2014 Phononic crystals and metamaterials—promising new sensor platforms Prociodia Engineering 87 40–5
[8] Maldovan M 2013 Sound and heat revolutions in phononics Nature 503 209–17
[9] Villa-Arango S, Sánchez D B, Torres R, Kyriacou P A and Lucklum R 2017 Differential phononic crystal sensor: towards a temperature compensation mechanism for field applications development Sensors 17 1960
[10] Mehaney A and Ahmed A M 2019 Locally resonant phononic crystals at low frequencies based on porous SiC multilayer Sci. Rep. 9 14767
[11] Guillén-Gallegos C, Alva-Medrano H, Pérez-Aguilar H, Mendoza-Suárez A and Villa-Villa F 2019 Phononic band structure of an acoustic waveguide that behaves as a phononic crystal Results in Physics 12 1111–8
[12] Lucklum R and Li J 2009 Phononic crystals for liquid sensor applications Meas. Sci. Technol. 20 124014
[13] Salman A, Kaya O and Cicek A 2014 Determination of concentration of ethanol in water by a linear waveguide in a 2-dimensional phononic crystal slab Sensors Actuators A 208 50–5
[14] Olsson R III and El-Kady I 2008 Microfabricated phononic crystal devices and applications Meas. Sci. Technol. 20 012002
[15] Lucklum R, Li J and Zubtsov M 2010 1D and 2D phononic crystal sensors Prociodia engineering 5 436–9
[16] Amoudache S, Pennecc Y, Djafari-Rouhani B, Khater A, Lucklum R and Tigrine R 2014 Simultaneous sensing of light and sound velocities of fluids in a two dimensional phonic crystal with defects J. Appl. Phys. 115 134503
[17] Pennecc Y, Vasseur J O, Djafari-Rouhani B, Dobrzynski L and Deymier P A 2010 Two-dimensional phononic crystals: examples and applications Surf. Sci. Rep. 65 229–91
[18] Zubtsov M, Lucklum R, Ke M, Oseev A, Grundmann R, Henning B and Hempel U 2012 2D phononic crystal sensor with normal incidence of sound Sensors. Actuators A 186 118–24
[19] Armenise M N, Campanella C E, Ciminelii C, dell’Olio F and Passero V M N , 2009 Phononic and photonic band gap structures: modelling and applications Phys. Proc. 3 557–64
[20] Villa-Arango S, Torres R, Kyriacou P A and Lucklum R 2017 Fully-disposable multilayered phononic crystal liquid sensor with symmetry reduction and a resonant heterodyne Measurement 102 20–5
[21] Ke M, Zubtsov M and Lucklum R 2011 Sub-wavelength phononic crystal liquid sensor J. Appl. Phys. 110 026101
[22] Aly A H, Nagaty A and Mehaney A 2018 Thermal properties of one-dimensional piezoelectric phononic crystal Eur. Phys. J. B 91 251
[23] Pennecc Y, Jin Y and Rouhani B D 2019 Phononic and photo phononic crystal for sensing application Adv. Appl. Mech. 52 105
[24] Sharma G, Kumar S and Singh V 2017 Design of Si–SiO2 phononic crystal having defect layer for simultaneous sensing of biodiesel in a binary mixture of diesel through optical and acoustic waves Acoust. Phys. 63 159–67
[25] Mehaney A 2019 Biodiesel physical properties detection using one-dimensional phononic crystal sensor Acoust. Phys. 65 374–8
[26] Lucklum R, Zubtsov M, Oseev A, Schmidt M and Hirsch S 2016 SAW based sandwich phononic crystal sensor *Procedia Engineering* **168** 700–3
[27] Knothe G and Razon L F 2017 Biodiesel fuels *Prog. Energy Combust. Sci.* **58** 36–59
[28] Mohd Noor C W, Noor M M and Mamat R 2018 Biodiesel as alternative fuel for marine diesel engine applications: a review *Renew. Sustain. Energy Rev.* **94** 127–42
[29] Sonthalia A and Kumar N 2019 Hydroprefoccessed vegetable oil as a fuel for transportation sector: a review *J. Energy Inst.* **92** 1–17
[30] Tat M E and Gerpen J H V 2003 Measurement of Biodiesel Speed of Sound and Its Impact on Injection Timing, NREL/SR-510-31462.
[31] Sidibe S S, Blin J, Vaitilingom G and Azoumah Y 2010 Use of crude filtered vegetable oil as a fuel in diesel engines state of the art: literature review *Renew. Sustain. Energy Rev.* **14** 2748–59
[32] Ma F and Hanna M A 1999 Biodiesel production: a review *Bioresour. Technol.* **70** 1–15
[33] Capuano D, Costa M, Di Fraia S, Massarotti N and Vanoli L 2017 Direct use of waste vegetable oil in internal combustion engines *Renew. Sustain. Energy Rev.* **69** 759–70
[34] Demirbas A 2008 *Biodiesel A Realistic Fuel Alternative for Diesel Engines* (London: Springer)
[35] Li Chen A and Wang Y S 2007 Study on band gaps of elastic waves propagating in one-dimensional disordered phononic crystals *Physica B* **392** 369–78
[36] Hussein M I, Hulbert G M and Scott R A 2006 Dispersive elastodynamics of 1D banded materials and structures: analysis *J. Sound Vib.* **289** 779–806
[37] Arango S V, Sánchez D B, Torres R, Kyriacou P and Lucklum, R 2017 Differential phononic crystal sensor: towards a temperature compensation mechanism for field applications development *Sensors* **17** 1960
[38] Arango S V, Betancur D, Torres R and Kyriacou, P 2018 Use of transient time response as a measure to characterize phononic crystal sensors *Sensors* **18** 3618
[39] Chen Y, Dong J and Liu T 2016 Refractive index sensing performance analysis of photonic crystal containing graphene based on optical Tamm state *Modern Physics Letters B* **30** 1650030
[40] Lucklum R, Zubtsov M and Arango S V 2014 Cavity resonance Biomedical Sensor Proc. of the ASME 2014 Int. Mechanical Engineering Congress and Exposition IMECE 14–20 (Montreal, Quebec, Canada)