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1 Thermoacoustic refrigerator driven by a 2 combustion-powered thermoacoustic engine for 3 rural communities

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15 **Abstract.** The purpose of the current study is to present the potential of
16 using coupled thermoacoustic engine/cooler in looped-tube topologies to be
17 incorporated into designs of cookstoves in developing countries. This can be
18 applied for storing vital medical supplies such as vaccines or agricultural
19 produce in remote and rural communities. The usage of cookstoves in two
20 sample rural communities of Mexico and Uganda is presented. Additionally,
21 the low-cost coupled thermoacoustic engine/refrigerator system is
22 demonstrated. The lowest temperature of -3.6°C, operating at frequency of
23 58.6 Hz, was achieved at the cold end of the refrigerator. Further numerical
24 analysis of the thermoacoustic prototype is carried out to achieve a higher
25 cooling performance. With the substantial adjustment, both regenerators of
26 engine and refrigerator operate in the travelling wave phasing region with
27 high acoustic impedance. The acoustic field in the system is also
28 significantly improved. This will contribute to a better cooling performance
29 of the system.

30 1 Introduction

31 Remote and rural communities in developing countries, especially in Africa and Asia, often
32 face problems of no access to electrical energy. However, often they also require access to
33 refrigeration capabilities for storing vital medical supplies such as vaccines or agricultural
34 produce. In their daily life, the people in these societies cook on open fires with biomass
35 burning, e.g. wood, charcoal, sawdust, etc [1]. This work aims at addressing the refrigeration
36 needs by application of thermoacoustic technologies where thermal input from biomass

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37 combustion can be used to directly generate acoustic power (in a thermoacoustic engine),
38 which in turn can be converted to cooling power (in a coupled thermoacoustic refrigerator).

39 The energy conversion between thermal and acoustic energies relies on a thermoacoustic
40 effect where the oscillation of a compressible working fluid in the vicinity of a solid material
41 provides a means for designing thermodynamic cycles. Such technology is considered very
42 attractive due to its reliability, low maintenance and environmental friendliness.
43 Thermoacoustic devices can be classified into “engines” and “refrigerators/coolers/heat
44 pumps”. The thermoacoustic engine converts thermal energy into acoustic energy.
45 Conversely, the thermoacoustic refrigerator employs an acoustic wave imposed along the
46 solid material to generate the temperature gradient [2]. In recent years, there has been an
47 increased research on the combined configuration of the thermoacoustic engine and
48 refrigerator. The generated acoustic power from the engine can be supplied directly to
49 produce the heat pumping effect in the refrigerator. The thermoacoustic refrigerator driven
50 by the thermoacoustic engine also has particular advantages in using low-quality heat source
51 or renewable energy, such as industrial waste heat, solar energy or flue gases from the
52 combustion processes for energy recovery [3-6].

53 A demonstrator of a looped-tube travelling-wave thermoacoustic refrigerator driven by
54 combustion-powered thermoacoustic engine has been developed [4]. It can be particularly
55 beneficial for residents in remote and rural communities, where large quantities of waste heat
56 are generated daily through biomass combustion in cookstoves. When such waste heat is
57 harnessed to drive a cooling cycle it can be of immense benefit to improve the quality of
58 healthcare by immediate access to vital medicines.

59 The purpose of the paper is two-fold: Firstly, to outline typical examples of cookstoves
60 and their usage in two rural sample communities of Mexico and Uganda. Secondly, to explore
61 the possibilities of using looped-tube topologies for coupled thermoacoustic
62 engine/refrigerator to be incorporated into such cookstove designs. The prototype as
63 discussed in [4] used standard inexpensive parts and employed air at atmospheric pressure as
64 working fluid. The testing showed that the lowest temperature of -3.6°C was achieved at the
65 cold end of the refrigerator. In the desired medicine storage temperature of $+2$ and $+8^{\circ}\text{C}$, the
66 system produced a cooling load between 3 and 7 W. Several aspects of the design are
67 intensively examined for enhancing the cooling power by improving the phase difference
68 between pressure and volumetric velocity, selecting suitable regenerators, and investigating
69 the optimum position of the matching stub. This is demonstrated by modelling the system in
70 DeltaEC programme. The cooling performance before and after the improvement is
71 presented, and the changes to the acoustic field are examined.

72 **2 The usage of cookstoves in rural communities**

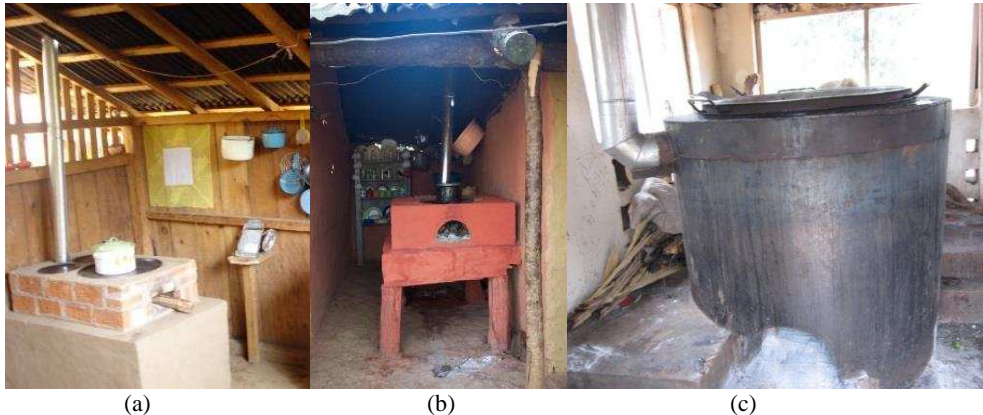
73 By way of illustration, it is worth mentioning two countries where use of cookstoves is
74 relatively widespread: Mexico and Uganda. Biomass accounts for 10% of final energy use
75 and 40% of residential energy use in Mexico. It is estimated that about 22.5 million people
76 (or near 20% of Mexican total and 90% of rural population) still used fuelwood (FW) for
77 cooking in open fires in 2010. Approximately 16.8 million people are exclusive users, and
78 5.7 million uses wood in combination with LPG (mixed use) to cover their cooking and other
79 basic needs. Total fuelwood use reaches 310 PJ/yr or 40% of total residential sector energy
80 use (763 PJ) [7].

81 Figures 1(a) and 1(b) illustrate two designs of cookstoves with chimney stacks where a
82 significant amount of waste heat is discharged without making any use of it. Currently there
83 are more than 100 stove manufacturers in Mexico, ranging from small-scale regional
84 enterprises, to large-scale international manufacturers. Improved cookstoves in Mexico all
85 come with a chimney and a flat pan to cook tortillas. They can be made of metal, or local

86 materials such as brick, cement and mud. There is therefore a lot of potential to incorporate
87 cooler/refrigeration or electricity generation facilities (or both) as either a retrofit to existing
88 designs or within the design of new stoves marketed in Mexico, for example within the
89 government “top-down give-stoves-for-free approach” adopted by Mexican government
90 within its Improved CookStove (ICS) programmes for rural communities.

91 The Ugandan energy sector is dominated by biomass, accounting for 92% of the energy
92 use, followed by petroleum (6%) and electricity (2%) [8]. Biomass consumption comes from
93 firewood, charcoal and crop residues. It provides all the basic needs for cooking and water
94 heating in rural areas and for most urban households. The National Population and Housing
95 Census 2014 [9] shows that biomass (wood and charcoal) are still used as main sources of
96 energy for cooking by the vast majority of Ugandan households (94%). Use of electricity
97 (2%) and gas (1%) is still very low, while about 3% of households use alternative fuel sources
98 (biogas, cow dung, etc.) for cooking. Rural communities mainly use firewood (85%),
99 followed by charcoal (12%), while urban communities show the opposite: charcoal (58%) as
100 major energy source, followed by firewood (31%).

101 Ugandan manufacturers mainly rely on artisanal production methods which, though
102 cheap, negatively affect product consistency and quality. There are a number of industrially
103 produced cookstoves on the market, but they are all imported and at a higher price level.
104 Highly advanced cooking solutions are available, though their penetration rate is currently
105 quite low. However, the adoption by specific market segments of these modern cookstoves,
106 that provide a combination of cooking, lighting and charging of mobile devices, may offer a
107 good entry point for thermoacoustic devices in Uganda. Figure 1(c) illustrates an institutional
108 stove at a prison facility in Uganda with a chimney stack where large quantities of waste heat
109 are disposed to the atmosphere.
110



113 **Fig. 1.** Examples of cookstoves with chimney stacks: (a) and (b) rural dwellings in Mexico; (c)
114 institutional stove at a prison’s facility in Uganda

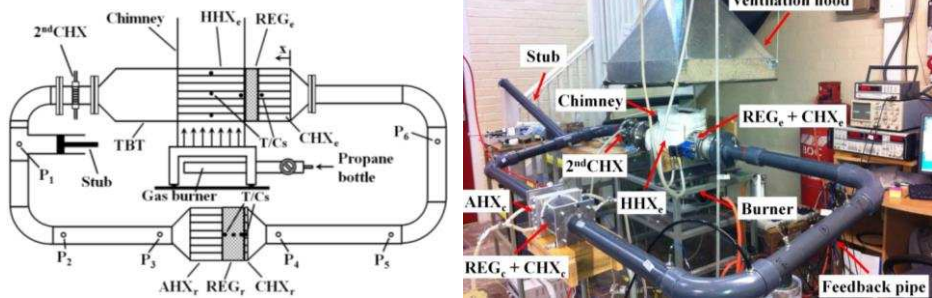
115 **3 The coupled thermoacoustic engine/refrigerator**

116 A prototype of looped-tube travelling wave thermoacoustic refrigerator driven by
117 combustion-powered thermoacoustic engine [4] was developed. The system was designed
118 with the requirements of a simple structure and low-cost device. The important design issues
119 including type of the device, operating pressure, working fluid, material and configuration of
120 each component are considered under those constrains.

121 To meet the simplicity and low-cost point of view, air at atmospheric pressure was
122 selected as working fluid because of its availability. A one-wavelength looped-tube travelling

123 wave structure was designed because of providing relatively efficient energy conversion.
 124 Such a relatively simple arrangement could be implemented as a practical solution. In
 125 addition, an extra phase tuning component namely “a matching stub” was introduced into the
 126 system to improve the impedance matching of a “coupled” engine/refrigerator system. The
 127 matching stub is to shunt part of the velocity away from the resonator to compensate the
 128 acoustic impedance increase caused by the existence of the refrigerator inside the loop [10].

129 The schematic diagram of the system is presented in Fig. 2. There are two subsystems:
 130 the engine and the refrigerator, located in the same loop of a travelling wave type. The engine
 131 is powered by flue gases. It comprises of cold heat exchanger (CHX_e), regenerator (REG_e),
 132 hot heat exchanger (HHX_e), thermal buffer tube (TBT) and secondary cold heat exchanger
 133 ($2^{nd}CHX$). The refrigerator is located opposite to the engine and consists of an ambient heat
 134 exchanger (AHX_r), regenerator (REG_r) and cold heat exchanger (CHX_r). In addition, the side
 135 branch matching stub is used while the feedback pipes complete the loop. The total loop
 136 length is 4.969 m corresponding to an operating frequency of 58.6 Hz. Subscripts “e” and “r”
 137 refer to the engine and refrigerator, respectively. The coordinate x describing the distribution
 138 of components within the loop for modelling starts from the cold heat exchanger of the engine
 139 (CHX_e); $x = 0$.



140
 141 **Fig. 2.** Schematic diagram (left) and laboratory implementation (right) of the system [4]

142 In the thermoacoustic engine, the CHX_e is made from a round aluminium block which is
 143 90 mm long and has 110 mm diameter. The porosity of the CHX_e is about 9.3%. The REG_e
 144 is made out of stainless screen disks with the diameter of 110 mm and the wire diameter of
 145 0.16 mm. The length of the REG_e is 23 mm. The porosity and hydraulic radius of the REG_e
 146 are 82% and 196 μm , respectively. Two Type-K thermocouples are installed at the two ends
 147 of the REG_e to monitor the temperature difference. The HHX_e has a shell-and-tube
 148 configuration and has a length of 160 mm. It is heated by the combustion process. Three
 149 Type-K thermocouples are placed in the HHX_e to monitor the solid temperature of the tube
 150 wall. The TBTs are located between the HHX_e and $2^{nd}CHX$ to suppress the heat leaks. The
 151 $2^{nd}CHX$ is added to remove the excess heat from hot air. A “matching stub” is connected to
 152 the loop through a T-junction to improve the acoustic impedance matching between the
 153 engine and the refrigerator. The stub length is much less than a quarter of the wavelength.

154 In the thermoacoustic refrigerator, the AHX_r is also made out of an aluminium block
 155 which is 110 mm in diameter and 60 mm long. The porosity of the AHX_r is 32%. The REG_r
 156 is a stack of stainless steel mesh screens with mesh number 34 and the wire diameter 0.254
 157 mm. The disks form a 30 mm long regenerator with a diameter of 110 mm. The porosity and
 158 hydraulic radius are 73.31% and 174.4 μm , respectively. Three Type-K thermocouples are
 159 mounted at the two ends and in the middle of the REG_r to observe the temperature
 160 distribution. The Ni-Cr resistance wire is situated at the cold side of the REG_r to act as a
 161 cooling load. The electrical power is supplied to the heater wires by a DC power supply. One
 162 Type-K thermocouple is fixed at the position of the heating wire to monitor the changes of
 163 temperature as the cooling load changes. There are six pressure transducers (PCB

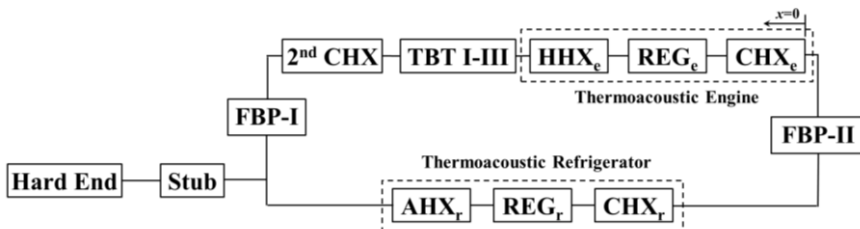
164 PIEZOTRONICS model 122A22) placed around the loop (marked P1 to P6 in Fig. 2) to
165 measure the pressure amplitude, phase angle and frequency. The feedback pipe (FBP) is
166 made of standard 2-inch PVC pipe and 90° bends instead of a metal pipe to reduce cost.

167 In the experiments, the resonance frequency of the coupled system is 58.6 Hz. The lowest
168 temperature of -3.6°C can be achieved at the cold end of the refrigerator with zero cooling
169 load. In the desired temperature of +2 and +8°C for storing vital medicines, the system is
170 capable of producing the cooling load between 3 and 7 W. Overall, the prototype would be able
171 to produce a small amount of cooling capacity for storing the vital medicines [11].
172 Furthermore, the simulation also reported that the REG_e operates in the region of $-54.7^\circ < \phi < -$
173 61.7° , and the impedance phase of REG_r is in the region of $-30.5^\circ < \phi < -16.0^\circ$. Theoretically,
174 the regenerator must be located within the region of travelling phasing ($-45^\circ < \phi < +45^\circ$) [12].
175 This can imply that the coupled system is non-ideal travelling wave condition to operate.
176 This will of course affect the thermo-to-acoustic conversion or vice versa. To enhance the
177 system performance, there are a number of issues that would need to be implemented. More
178 specifically, these include tuning the acoustic network to improve the phase difference,
179 selecting suitable regenerators, and investigating the optimum positions of the refrigerator
180 and matching stub. These issues are demonstrated by modelling the coupled system in the
181 DeltaEC programme. The acoustic field along the device is also examined. The obtained
182 results from the present model are compared to those from the previous study [4].

183 4 DeltaEC simulation

184 In order to improve the cooling performance of the system, the optimisation process is
185 performed using a specialized design tool namely DeltaEC [13]. Its calculation capabilities
186 and precision in modelling thermoacoustic devices have been widely validated [14,15].
187 DeltaEC solves the one-dimensional wave equation based on the usual low-amplitude
188 acoustic approximation. A solution is found for each segment, with pressures and volume
189 flow rates matched at the junctions between segments. In the regenerators, the wave equation
190 is solved simultaneously with the energy-flow equation in order to find the temperature
191 profile as well as the acoustic field. The energy flowing through the regenerator is determined
192 by temperatures and/or heat flows at adjacent heat exchangers.

193 In the current work, DeltaEC is used to simulate the acoustic field and the acoustic power
194 flowing in the system. The phase angle between the acoustic pressure and velocity is tuned
195 to achieve the travelling wave phasing. These issues are examined numerically, i.e. better
196 matched regenerators, position and length of the stub, position of the refrigerator, etc. A block
197 diagram of the segments in DeltaEC simulation is shown in Fig 3 (c.f. Fig. 2). The simulation
198 for the thermoacoustic device is from the origin along the established coordinate through
199 each segment, with pressures and volumetric velocities matched at the junctions between
200 segments.



201
202 **Fig. 3.** The block diagram of the segments in DeltaEC simulation

203 The calculations are carried out under the conditions as follows: air is applied as working
204 gas, the mean pressure is 1 bar, the hot end temperature of the engine is maintained at 700 K

205 and the cooling load is zero. The temperatures of all AHXs are kept at 297 K. The total length
 206 of the present model remains the same as the previous study at around 5 m. The optimisation
 207 process is subsequently executed to achieve the lowest cooling temperature of the refrigerator
 208 whilst the travelling wave phasing in both REGs is accomplished. The procedure of
 209 optimisation is performed based on the multivariable search method by varying the values of
 210 the parameters in each component.

211 5 Results and discussion

212 The simulation results discussed in this section are based on the optimised values. The
 213 comparison results between the current model and the previous study [4] are highlighted in
 214 Table 1. It can be seen that the pressure amplitude ($|p_1|$) and volumetric velocity amplitude
 215 ($|U_1|$) are improved significantly after further modification. Therefore, the acoustic power
 216 flowing in the system is also elevated. These increased outcomes are influenced by the
 217 improved acoustic impedance phases of both REGs. As can be seen from Table 1, the average
 218 phase angles in both REGs, which are -7.0° and 5.5° in the REG_e and REG_r , respectively, are
 219 close to the ideal travelling wave phase ($\phi = 0^\circ$). This corresponds to the increase of thermo-
 220 acoustic efficiency of the engine, as well as the lower cooling temperature of the
 221 refrigerator.

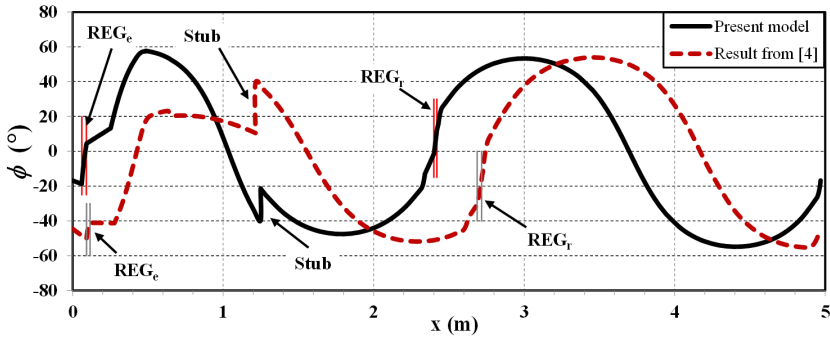
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Table 1. The simulation results

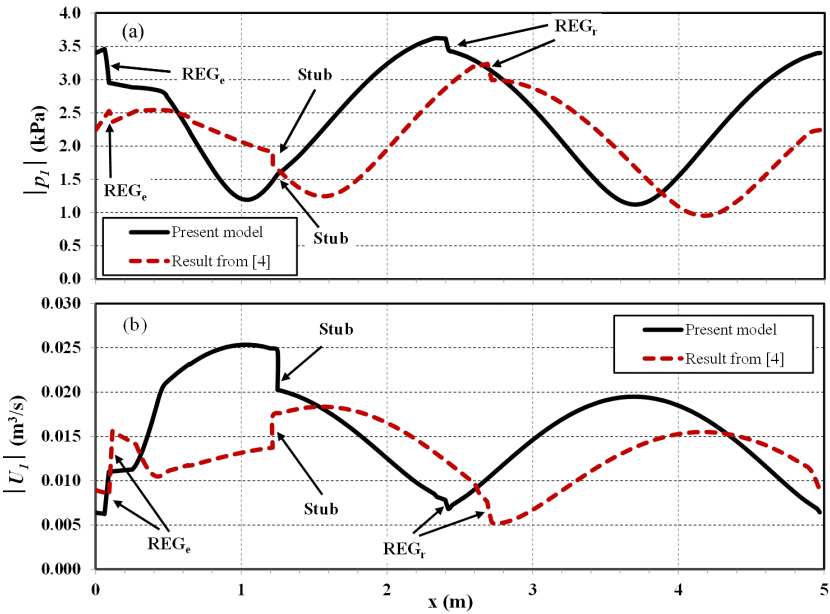
Parameters	The prototype in ref. [4]	Results from current study
Length of CHX_e	9 cm	6 cm
Position of REG_e	$x = 0.104$ m	$x = 0.076$ m
Length of REG_e	2.3 cm	3 cm
r_h of REG_e	115.2 μm	196 μm
Position of the stub	$x = 1.215$ m	$x = 1.2486$ m
Position of REG_r	$x = 2.7025$ m	$x = 2.4105$ m
Length of REG_r	3 cm	2 cm
r_h of REG_r	100 μm	120 μm
Pressure amplitude $ p_1 $	3.23 kPa	3.62 kPa
Velocity amplitude $ U_1 $	0.018 m^3/s	0.025 m^3/s
Impedance phase of REG_e	$-54.7^\circ < \phi < -61.7^\circ$	$-17.97^\circ < \phi < 3.90^\circ$
Impedance phase of REG_r	$-30.5^\circ < \phi < -16.0^\circ$	$-1.42^\circ < \phi < 12.47^\circ$
Efficiency of engine ($\Delta E/Q_{in}$)	5.46%	5.66%
T_{min} of the refrigerator	269 K	256 K

223 Fig. 4 presents the phase differences between pressure and velocity oscillating along the
 224 system. In the present study, the REG_e works in the region of $-17.97^\circ < \phi < 3.90^\circ$ and the
 225 REG_r also operates in the range of $-1.42^\circ < \phi < 12.47^\circ$ both of which are in the ideal travelling
 226 wave phase condition. Under the substantial adjustments, the phase differences in both REG_e
 227 and REG_r are improved significantly.

228 The distributions of pressure and volumetric velocity amplitudes along the system are
 229 presented in Fig. 5. It can be seen that the system performs as one-wavelength mode. The
 230 REGs are situated near the maxima of pressure amplitude or minima volumetric velocity
 231 amplitude in both models. The high acoustic impedance (ratio of acoustic pressure to
 232 velocity) is preferred in the REG to avoid high viscous dissipation. The sharp pressure drops
 233 at the REG_e and REG_r are observed due to the flow resistance of the stacked mesh screen.
 234 The present model can give a higher pressure amplitude which is up to 3.62 kPa.



235
236 **Fig. 4.** The distribution of phase differences between pressure and velocity along the system



237
238 **Fig. 5.** The distribution of the acoustic field along the system: (a) the pressure amplitude, and (b) the
239 volumetric velocity amplitude

240 Fig. 6 illustrates the acoustic power flowing along the system. In the present model, the
241 acoustic power distributed in the system is higher. Initially at $x=0$, about 10.4 W of acoustic
242 power is fed into the engine, and then amplified to around 16.4 W. Therefore, the engine can
243 produce a net acoustic power of about 6 W at an input heat power of 106 W, corresponding
244 to a thermo-to-acoustic conversion efficiency of 5.66%.

245 The HHX_e, TBT and 2ndCHX dissipate around 1 W of acoustic power. The acoustic power
246 of 0.3 W is dissipated in the stub, which is much less than that of the previous model. The
247 reason might be that the change of cross-sectional area of stub in the previous model is
248 eliminated. Consequently, the acoustic power of 2.7 W is consumed by the refrigerator to
249 pump heat from the cold-end to the ambient-end of the REG_r. The lowest temperature of
250 250.7 K can be achieved at no-load condition.

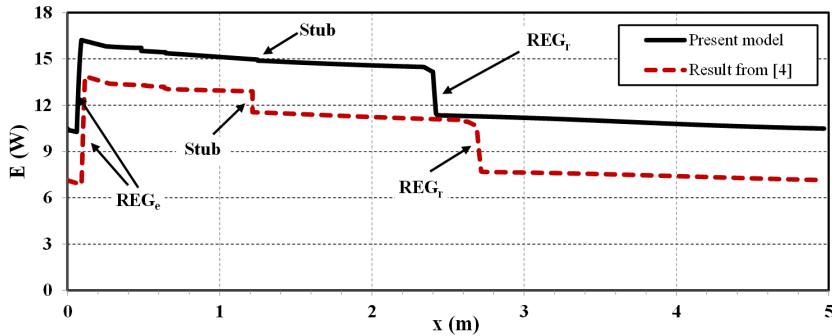


Fig. 6. The distribution of the acoustic power flowing along the system

6 Conclusions

The “coupled” configuration of the thermoacoustic engine and refrigerator in a looped-tube is studied in this work. This prototype has a high potential to be implemented for the cooling application in remote and rural area. The system is developed to be a low-cost and simple device. Formerly, the prototype was constructed and tested. The lowest cooling temperature of $-3.6\text{ }^{\circ}\text{C}$ was produced. The experimental results indicate that this system is able to produce enough cooling power for storing small quantities of vital medicines in remote and rural areas of developing countries. However, various parameters of the prototype require further optimisation in order to obtain a higher cooling performance. Therefore, this study demonstrates further improvements of this prototype by modelling the coupled system in the DeltaEC programme. The numerical results show that after adjustment both regenerators of engine and refrigerator operate in the travelling wave phasing region with high acoustic impedance. The acoustic field in the system is also significantly improved. This contributes to a better cooling performance of the system. Further experimental investigations on the modified system are needed in order to validate the simulation results from this study.

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