Exergy destroyed in the arteries due to stenosis

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ABSTRACT

Arteries can be compared to industrial pipes, being also susceptible to local pressure drops that may occur due to narrowing of the artery at some point, which is called stenosis. This phenomenon is taken as a singularity in the blood flow that leads to a localized head loss and, consequently, irreversibilities. In the present work, the exergy destruction in a given artery due to a stenosis is determined as a function of the diameter reduction taking into account the exergy variation of the flow between the inlet and the outlet, caused by distributed and localized head losses. The contribution of the stenosis is determined based on experimental results available in the literature. Arteries located in four different segments of the body are evaluated: trunk, leg, arm and neck. From the results, it can be noted that the effect of the severity of the stenosis is more pronounced for reductions higher than 55\%. From this point on, the exergy destruction increases exponentially. It is also observed that, despite showing different behaviors for individual parcels, the total destroyed exergy rate of stenotic arteries of the leg and the trunk are very similar for high severities. Meanwhile, the arm presents the lowest values. About the contribution of the stenosis to the total destroyed exergy, the segment less susceptible was the trunk. When the specific destroyed exergy due to the stenosis is analyzed, it becomes clearer the impact of the mass flow rate. In this case, the highest values are obtained in the leg, followed by the neck, the trunk and the arm.

Key words: exergy analysis; second law; human body; circulatory system; head loss

1. Introduction

As any other energy conversion process, those that take place in human body also need to be evaluated thermodynamically, and not only by the light of the First Law, but also by the Second one. Therefore, the application of the exergy analysis to the human body seeks to help understanding the energetic processes that remain unclear in medical area due to the difficulties of \textit{in vivo} studies. The ultimate goal of this research field is to enhance the knowledge of ageing and pathological processes, aiming at proposing indexes to evaluate the different conditions that the body experiences along lifespan.

Exergy analysis has been applied to the human body in studies of different areas, such as thermal comfort, physical activity performance, ageing and, finally, pathologies. The first author to perform the exergy balance of the body was Batato [1], and he concluded that the most relevant variable in this kind of analysis is the metabolic exergy. In the field of thermal comfort, Prek [2, 3], Prek and Butala [4], Simone et al. [5] and Mady et al. [6] related the environmental conditions of minimum destroyed exergy in the body to the thermal comfort zone. Eventually, Mady et al. [7], by applying the exergy analysis to the body during physical exercise, observed that the exergy efficiency is a function of exercise intensity and age. As the research field evolved, some authors began to apply the exergy analysis to smaller control volumes, such as the respiratory system [8, 9].
Meanwhile, concepts of the Second Law of Thermodynamics were also applied in an attempt to elucidate the ageing process. Based on the rate of living theory [10], Hershey [11] and Silva & Annamalai [12] claimed that there is a maximum cumulative value of entropy that can be generated throughout lifespan. Therefore, they proposed that entropy generation would be a variable more suitable than time to evaluate the stages of life progression. Following the same approach, Mady et al. [13] determined the specific cumulative destroyed exergy as a value around 3500MJ/kg for a standard healthy subject under sedentary condition. In addition to the study of the ageing process, Henriques et al. [14] performed the first attempt to evaluate how a non-standard condition, in this case, obesity, could affect the exergy performance of the human body, especially the cumulative destroyed exergy, which was established as the key variable for the assessment of life expectancy. The effects of obesity were evaluated by altering the composition of the model of the human body in order to simulate the increase of weight and body fat, disregarding the existence of other pathologies. Their results showed that the rate of living theory, which says that, among the same class, “larger animals live longer” [10] is also true for human species. However, the same results are conflicting with statistical data of mortality among obese population [15], meaning that the shorter life expectancy observed in this group is due to the development of obesity-related diseases, rather than to the sole presence of thicker fat tissue and higher metabolic rate. Therefore, in order to better assess the impact of obesity on exergy behavior and lifespan, the same research group decided to evaluate separately the cardiovascular system, given its key role in the death of obese people [16, 17]. First, Henriques et al. [18] presented an exergy model of the human heart able to evaluate both normotensive and hypertensive conditions for different levels of exercise. The results showed that both exercise and hypertension increase exergy destruction in the human heart due to blood pressure augmentation and consequent increment of pumping power and exergy of metabolism. Furthermore, this increase in hypertensive heart, when integrated along life cycle, represents 170MJ/kg of destroyed exergy, which, according to the exergetic age index, would cause a reduction of 4.4 years in life expectancy.

Hypertension is categorized by medical area as an idiopathic pathology, which means that its origin is unknown or spontaneous. On the other hand, it is known that, depending on the type of diet, some people can accumulate fat in the walls of the arteries, what may contribute to the development of arterial stenosis. The last term defines a localized constriction in an artery [19], which, analogously to what happens in industrial pipes, can be taken as a singularity of the flow that leads to an additional head loss. What remains unclear is if the need to overcome this head loss is enough to raise the mean arterial pressure. However, it is known that the presence of singularities along the flow increases the irreversibilities of the process. Thus, this work aims at evaluating the impact of a stenosis on the destroyed exergy of some segments of artery located on different parts of the body. Firstly, the pressure drops due to the stenosis are determined as a function of its severity, which is calculated from values of diameter reduction, based on experimental results available on the literature [20]. Then, the destroyed exergy in the segment is determined taking into account the difference of the exergy of the flow between the inlet and the outlet. The distributed head loss due to friction is also determined, as well as the contribution of the stenosis to the total head loss of the blood flow. It is important to highlight that this is the first attempt to evaluate, from the Second Law perspective, the effect of a fat-related disease.

2. Methods

2.1 Exergy model

The arteries are responsible for transporting oxygenated blood from the heart to the organs and, as well as in industrial pipes, the flow is subjected to distributed and localized head losses and, consequently, irreversibilities. The former results from the friction between the fluid and the surface and is a function of flow parameters [21]. Meanwhile, the latter occurs due to the presence of obstacles to the flow, which leads to the appearance of drag forces. In the case of the circulatory
The punctual narrowing of the arteries can cause localized head losses. The so-called stenosis can arise as a consequence of fat deposits, arterial coarctation and calcification, among others, and its level of severity is evaluated by means of the percentage diameter reduction. According to the literature, an artery with stenosis experiences a dilation in its diameter after the narrowing [20, 22], as depicted in Fig. 1.

\[
\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 + H_f + H_l
\]  

(1)

Furthermore, head losses lead to irreversibilities into the flow, boosting the exergy destruction. According to Kotas [23], the difference between the specific exergy flow \(b\) of points 1 (upstream) and 2 (downstream) of a flow is:

\[b_1 - b_2 = -b_Q + w + b_d\]  

(2),

where, \(w\) stands for the specific work, \(b_d\) is the specific destroyed exergy and \(b_Q\) is the specific exergy transfer associated to heat, which, in the case of an artery, is the heat exchange between the artery and its adjacent vein. Defining the control volume as a part of the artery that does not comprise the heart, \(w\) is zero and (2) can be written as follows.

\[b_d = b_1 - b_2 + b_Q\]  

(3)

The difference of the specific exergy flow is shown in (4), where \(h\) is the specific enthalpy, \(T_0\) stands for the reference temperature and \(s\) represents specific entropy.

\[b_1 - b_2 = h_1 - h_2 - T_0(s_1 - s_2) + \frac{V_1^2 - V_2^2}{2} + g(Z_1 - Z_2)\]  

(4)

Assuming the blood as an incompressible fluid, at constant temperature and not susceptible to changes in chemical composition, the difference of enthalpy between two points is given by

\[h_1 - h_2 = T(s_1 - s_2) + \frac{p_1 - p_2}{\rho}\]  

(5)

Substituting (5) in (4) it is possible to obtain

\[b_1 - b_2 = \frac{p_1 - p_2}{\rho} + \frac{V_1^2 - V_2^2}{2} + g(Z_1 - Z_2) + (T - T_0)(s_1 - s_2)\]  

(6)

Furthermore, by replacing (6) in (3), the specific destroyed exergy is given by
\[ b_d = \frac{p_1 - p_2}{\rho} + \frac{V_1^2 - V_2^2}{2} + g(Z_1 - Z_2) + (T - T_0)(s_1 - s_2) + b_Q \quad (7) \]

The specific exergy associated to the heat transfer between an artery and its corresponding vein is calculated as the product of the heat transfer per unit mass \((q)\) and the Carnot factor, which is equal to \((1 - \frac{T_o}{T})\). For a control volume, assuming steady state and only one inlet and outlet:

\[ s_1 - s_2 = -\left(\frac{q}{T} + s_g\right) \quad (8) \]

where \(s_g\) is the entropy generated internally. By replacing the expressions of \(b_d\) and \(s_1 - s_2\) in (7), the specific destroyed exergy can be calculated as follows.

\[ b_d = \frac{p_1 - p_2}{\rho} + \frac{V_1^2 - V_2^2}{2} + g(Z_1 - Z_2) + (T_0 - T)s_g \quad (9) \]

According to Gouy-Stodola theorem, \(b_d = T_0s_g\) and going back to (1), the first three terms on the right hand side of (9) may be replaced by \(q(H_f + H_l)\). Thus, the entropy generated is given by means of (10), where it becomes explicit that the irreversibilities present in blood flow are associated only to the head loss caused by friction between the blood and the artery walls and the drag forces due to any local obstacle, like a stenosis.

\[ s_g = \frac{q}{T}(H_f + H_l) \quad (10) \]

Then, the destroyed exergy rate in a stenotic artery, from this point on represented by \(B_{d,\text{total}}\), is calculated from (11). The first term on the right hand side is the parcel due to friction, which is present in every artery, healthy or not, represented by \(B_{d,\text{hth}}\). The second one takes into account the destroyed exergy due to the presence of a stenosis, represented by \(B_{d,\text{hth}}\). It should be emphasized that blood flow was assumed as continuous and steady, in spite of the pulsatile characteristic of heart cycle. Mean values of the variables along the cardiac cycle are taken into account in the calculus. The temperature \(T\) is assumed as the internal temperature of the body, taken as 36.5°C (309.7K). It should be pointed out that, if the control volume was external, \(T = T_0\) and \(B_{d,\text{total}}\) would not be a function of the temperature. Moreover, the term \((T - T_0)(s_1 - s_2)\) would not be present in the determination of the destroyed exergy in (7). However, for equal temperatures, the Carnot factor is zero and the \(B_Q\) vanishes from the equation anyway. Thus, regardless of temperature and heat exchange scenarios, the destroyed exergy is the energy measure of the head losses.

\[ B_{d,\text{total}} = \left(\frac{\dot{m}g}{T}T_0\right)H_f + \left(\frac{\dot{m}g}{T}T_0\right)H_l \quad (11) \]

The distributed head loss in the blood flow, which is a laminar one, is given in (12), where \(Re\) is the Reynolds number, \(L\) indicates the length and \(D\) stands for the diameter. Besides, the blood is assumed as a Newtonian fluid, which is a fair approximation for medium and large arteries [19]. The localized head loss may be computed by means of (13) as a function of the loss coefficient \(K\), which is dimensionless and determined experimentally [21].

\[ H_f = \frac{64}{Re} \left(\frac{L}{D}\right) \left(\frac{V^2}{2g}\right) \quad (12) \]

\[ H_l = K \frac{V^2}{2g} \quad (13) \]

In (14), the index \(R\) is proposed in order to evaluate the contribution of the stenosis to the total destroyed exergy in a stenotic artery.

\[ R = \frac{B_{d,\text{hth}}}{B_{d,\text{total}}} \quad (14) \]
2.2. Input data

The values of pressure drop in the presence of a stenosis are obtained from the study developed by Oshinski et al. [20], who performed a series of experiments involving both patients and rigid glass tube models able to reproduce the flow conditions of a stenosis. Models with different levels of stenosis severity were constructed and the pressures were measured at a distance of 2 diameters upstream of the necking and 10 downstream in order to take into account the effects of turbulence near the stenosis and pressure recovery on the pressure drop, making a total length of 0.3m. As shown in Fig. 2, the post-stenotic dilation was taken into account. The diameter in point 1 is 0.025m and 0.032m in point 2 and these values are used to determine the velocities, assuming constant blood flow. Flow velocity while passing through the stenosis was measured using a Doppler ultrasound device. Diameter reductions of 50%, 55%, 60%, 70%, 80% and 90% were evaluated.

The experiment above-mentioned was focused on determining the loss coefficient as a function of the severity. From the loss coefficients obtained by means of the experiment described previously, the pressure drop was calculated for real stenosis of known severities and the values were confronted to those obtained by in vivo measurements. The comparison showed a good agreement, validating not only the values of the loss coefficients, but also the assumption of the artery as a rigid tube, which is also assumed herein.

However, the loss coefficient assessed by Oshinski et al. [20] is physically different from the one expressed in (13), because the former is used to calculate the pressure drop and not the head loss. Moreover, the experiment was designed in a way that the pressure drop measured comprehends not only the effect of the stenosis, but also the one associated to friction. Thus, the values of loss coefficient available in [20] cannot be directly applied to equation (13) in order to obtain the localized head loss due to the stenosis. For that reason, from the data of the glass tubes and assuming the blood flow rate of an artery of the trunk, which has the measures closer to those of the experiment, the velocities in 1 and 2 were determined, as well as the head loss due to friction. With the help of equations (11-13), the loss coefficient $K$ was determined as a function of the severity $S$ of stenosis. By means of a linear regression, values of $K$ for severities from 15% to 90% were obtained, as shown in (15). The coefficient of determination of the regression is close to 1.

$$K = 1.6514 \cdot S - 0.2125 \quad (15)$$

In order to determine the destroyed exergy rate of stenotic arteries of trunk, neck, arm and leg the diameters and lengths of the main artery of each segment, as well as the blood flow rates, are taken from the study performed by Reymond et al. [24] and Özcan et al. [25].

3. Results and discussion

The exergy analysis was applied to stenotic arteries of different parts of the body and the main results are shown in Fig. 3 to 7. The total destroyed exergy rate of a stenotic artery is shown in Fig. 3a, where it is possible to observe that, for severities under 75%, $B_{d\text{total}}$ is closer to zero. From this
point on, the exergy destruction begins to increase exponentially, except in the arm, where the values are still smaller than 0.5 W. Due to the large range of data, the values are also presented in logarithmic scale in Fig. 3b. The trunk presents the highest $B_{d,total}$ value, however, for severities smaller than 55%, its value increases at a rate inferior to those presented by the other segments. From this point on, the total destroyed exergy of the leg equals the one of the trunk and the curves of all segments have the same rate of increment. $B_{d,total}$ in the neck is close to the values presented by the leg, while the arm presents the smallest ones.

![Fig. 3: Total destroyed exergy rate in stenotic arteries ($B_{d,total}$) as a function of severity shown in regular (a) and logarithmic (b) scales.](image)

The values of $B_{d,hth}$ are displayed in Table 2, as well as the head loss due to friction ($H_f$) and the mass flow rate ($\dot{m}$). $B_{d,hth}$ is the component of $B_{d,total}$ that is also present in a healthy artery and is a consequence of friction between the artery wall and the blood. Thus, $B_{d,hth}$ does not vary with stenosis severity and depends only of the characteristics of the artery and the flow. As can be observed in the last column of Table 2, the trunk shows the highest value of $B_{d,hth}$ while the arm has the lowest one. The arteries of the leg and the neck occupy the intermediate positions of the ranking. However, in comparison to the magnitude of $B_{d,total}$, all the segments present small values of $B_{d,hth}$. The order of magnitude of $B_{d,hth}$ in an artery of the trunk, which is the highest one, is of $10^{-4}$ W. The contribution of the destroyed exergy due to friction to the total value will be better analyzed further.

### Table 2: Value of distributed head loss ($H_f$), mass flow rate ($\dot{m}$) and destroyed exergy rate in a healthy artery ($B_{d,hth}$) for each segment of the body.

<table>
<thead>
<tr>
<th>Segment</th>
<th>$H_f$[m]</th>
<th>$\dot{m}$[kg/s]</th>
<th>$B_{d,hth}$[W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk</td>
<td>2.45E-03</td>
<td>2.11E-02</td>
<td>5.06E-04</td>
</tr>
<tr>
<td>Leg</td>
<td>2.45E-04</td>
<td>5.38E-03</td>
<td>1.29E-05</td>
</tr>
<tr>
<td>Neck</td>
<td>2.20E-05</td>
<td>6.85E-03</td>
<td>1.48E-06</td>
</tr>
<tr>
<td>Arm</td>
<td>1.88E-05</td>
<td>2.98E-03</td>
<td>5.05E-07</td>
</tr>
</tbody>
</table>

The other component of $B_{d,total}$ is the destroyed exergy due to the stenosis, which presents a large range of values. Thus, this variable is also shown in logarithmic scale in Fig. 4. The curves of all segments have the same shape and increase almost linearly with severity. About the values, the lowest ones occur in the arm, what, combined with the results of $B_{d,hth}$, explains its behavior for $B_{d,total}$. The coincidence of the curves of the trunk and the leg are noteworthy, taking into account that this happens for $B_{d,total}$ only for severities greater than 55% and also the low values of $B_{d,hth}$. For a diameter reduction of 15%, the order of magnitude of $B_{d,stan}$ for the trunk and the leg are of $10^{-5}$ W, one order smaller than that of $B_{d,hth}$ in the trunk and the same of the leg. For that reason, the
The difference of $B_{d,hth}$ for these segments plays a role on the behavior of $B_{d,total}$ for low severities. Furthermore, the coincidence of $B_{d,stin}$ in these two segments can be explained by the values of mass flow rate and specific destroyed exergy due to stenosis $b_{d,stin}$.

![Graph showing destroyed exergy rate due to the stenosis in logarithmic scale as a function of severity.](image)

**Fig. 4: Destroyed exergy rate due to the stenosis in logarithmic scale as a function of severity.**

In order to understand the behavior of the destroyed exergy rate due to the stenosis in the leg and in the trunk, the specific destroyed exergy due to the stenosis is plotted in Fig. 5, also in logarithmic scale. It can be observed that the value of $b_{d,stin}$ in an artery of the trunk is smaller than those of the leg and the neck. However, the mass flow rate in this artery, as shown in the third column of Table 2, is greater than in the other segments. Thus, when $B_{d,stin}$ is determined, its value in the trunk overcomes that of the neck and equals the one of the leg. As shown in (13), the determination of the head loss due to a singularity, in this case, a stenosis, is directly related to the velocity squared, which, in turn, is determined from the values of blood flow rate and cross sectional area of the artery. Thus, the highest velocity is observed in the artery of the leg, followed by the neck, the trunk and the arm. For that reason, the ranking for $b_{d,stin}$ is the same.

![Graph showing specific destroyed exergy due to the stenosis in logarithmic scale as a function of severity.](image)

**Fig. 5: Specific destroyed exergy due to the stenosis in logarithmic scale as a function of severity.**

Then, the contribution of the stenosis to the total destroyed exergy rate in a stenotic artery is evaluated by means of the index $R$, displayed in Fig. 6. In all segments of the body, the contribution of the stenosis comes close to 100% for severities greater than 70%. However, the path to get to this value is different for each part of the body. For low severities, the trunk presents the lowest contribution, while the other segments have values of $R$ greater than 60%. This behavior is associated to the higher value of $B_{d,hth}$ presented by this segment, which has an influence for low
severities. Despite of the difference presented for the other variables, the contribution of the stenosis for the leg and the arm are similar. On the other hand, the higher values of $R$ are expressed in the neck, because its $B_{d,\text{total}}$ is close to those of the trunk and the neck but the value of $B_{d,\text{nth}}$ in this segment is smaller.

![Graph showing contribution of the stenosis to the total destroyed exergy rate as a function of severity.](image)

**Fig. 6:** Contribution of the stenosis to the total destroyed exergy rate as a function of severity.

After all, the values of pressure drop along the stenosis, taking it as a localized head loss, are shown in Fig. 7. It should be clarified that $\Delta P$ is presented in mmHg instead of Pa because it is the conventional unit for measures of arterial pressures. The limit values of arterial pressures for a healthy subject are 140mmHg for systolic pressure and 90mmHg for diastolic one. The maximum mean arterial pressure for this subject is 106mmHg, value that is determined by means of a weighted average, where the systolic pressure has weight one and the diastolic one, two. Pressures above those numbers characterize hypertension. $\Delta P$ increases in a way similar to $B_{d,\text{total}}$ and $B_{d,\text{str}}$, so it is also presented in logarithmic scale in Fig. 7b. In Fig. 7a, the y-axis is limited to $\Delta P$ values of 106mmHg, in order to evaluate, in each segment, how the pressure drop increases towards the maximum value of mean arterial pressure in a normotensive subject.

![Graph showing pressure drop in stenotic arteries as a function of severity shown in regular (a) and logarithmic (b) scales.](image)

**Fig. 7:** Pressure drop in stenotic arteries as a function of severity shown in regular (a) and logarithmic (b) scales.

Extreme hypertension is characterized by values of mean arterial pressure around 132mmHg. Therefore, an additional pressure drop of 26mmHg would convert a normotensive subject in an extremely hypertensive one. The artery of the leg reaches the pressure drop of 26mmHg at a diameter reduction of 65%, followed by the neck, the trunk and the arm, with severities of 70%, 73% and 82%, following the same trend observed in $b_{d,str}$, since $\Delta P$ is determined from the values of head loss due to the stenosis. As a result, to pass through the stenosis of those severities, reach the other parts of the body and go back to the heart, the mean inlet pressure needs to be higher than
106mmHg, what characterizes a state of hypertension. Thus, more than an idiopathic disease, the hypertension should be treated as a warning that something is leading to additional pressure drops in the circulatory system, forcing the heart to provide more power in order to increase its outlet pressure and guarantee that the blood will reach all the organs properly.

Apart from the effects on blood pressure and work of the heart, the occurrence of a stenosis, as highlighted by Ku [26], is also related to structure alterations in the artery by increasing the shear stresses, what may cause an increment of platelets production. This combination of fluid, structural and physiological alterations can, ultimately, induce a thrombosis and prevent the blood from getting to the heart or the brain. For those reasons, it is important to evaluate and quantify well the effects of the stenosis.

**Conclusions**

By applying the exergy analysis to stenotic arteries of different segments of the body, it was noticed that the total destroyed exergy assumes relevant values only for severities greater than 75%. From this point on, the exergy destruction begins to increase exponentially. When looking at the results in a logarithmic scale, it becomes clear that the highest values are attributed to the trunk and the leg, followed closely by the neck and, then, the arm. The parcel of the destroyed exergy due to friction is constant for each segment and presents low values. The highest one, attributed to the trunk, has an order of magnitude of $10^{-4}$W. About the destroyed exergy due to the stenosis, the curves of the trunk and the leg are almost coincident for the whole severity range, what differs from the total destroyed exergy. For small severities, the order of magnitude of $B_{d,\text{total}}$ is as small as that of $B_{d,\text{hth}}$. Thus, for low severities, the higher value of $B_{d,\text{hth}}$ of the trunk has an impact, when compared to that of the leg. When the specific destroyed exergy due to a stenosis is determined, the arteries of the leg and the neck present higher values than the trunk. All segments of the body present high contributions of the stenosis to the total destroyed exergy, except the trunk, which has a higher destroyed exergy due to friction.

Finally, the pressure drop produced by a stenosis was analyzed aiming at correlating it to hypertension. From the analysis, it was observed that the additional pressure drop needed to cause extreme hypertension would occur in the leg at a diameter reduction of 65%, followed by the neck, the trunk and the arm, with severities of 70%, 73% and 82%. Thus, to pass through the stenosis of those severities, reach the other parts of the body and go back to the heart, the mean inlet pressure needs to be higher than the standard value, charactering a state of hypertension. Besides, more than an idiopathic disease, the hypertension should be treated as a warning that something is leading to additional pressure drops in the circulatory system, forcing the heart to provide more power in order to increase its outlet pressure and guarantee that the blood will reach all the organs properly. Moreover, a correct diagnosis of a stenosis may prevent the occurrence of thrombosis, which may have serious consequences in case of blocking the blood flow to the heart or the brain.

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**Nomenclature**

- $B$ exergy rate and flow rate, W
- $b$ specific exergy, J/kg
- $D$ diameter, m
- $g$ gravity acceleration, m/s$^2$
specific enthalpy, J/kg
head loss, m
loss coefficient
length, m
mass flow rate, kg/s
pressure, Pa
specific heat transfer, J/kg
contribution of stenosis to destroyed exergy
Reynolds number
severity
specific entropy, J/(kg.K)
temperature, K
velocity, m/s
specific work, J/kg
height, m
Greek symbols
specific mass, kg/m³
Subscripts and superscripts
reference
upstream
downstream
artery
between artery and vein
destroyed
distributed
associated to heat
localized
healthy
stenotic
total
References
[1] Batato M., Borel L., Deriaz O., Jequier, E., Analyse exergétique théorique et expérimentale
[4] Prek M., Butala, V., Principles of exergy analysis of human heat and mass exchange with the
B.W., A relation between calculated human body exergy consumption rate and subjectively


