WOOD RESEARCH
63 (5): 2018
809-820

# THE GRADIENT OF WOOD MOISTURE WITHIN-STEM OF SESSILE OAK (*QUERCUS PETRAEA* (MATT.) LIEBL.) IN SUMMER

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(Received March 2018)

## ABSTRACT

In the xylem of growing trees water fills both free spaces in the cell walls and capillary spaces. For this reason its share in the tree mass is very high. As a result transport of logs obtained from fresh-felled trees is mainly equivalent to the transport of contained water. The primary aim of this study was to determine wood moisture content in growing trees in the selected season of the year. Absolute moisture content of tested wood was established at 62.4%. Average moisture content in heartwood was 60.6% and it was lower by approx. 6% from moisture content in sapwood. Moisture content of the oak heartwood is high, similar to central part of the trunk of non – heartwood species. It is an exceptional situation in comparison to heartwood species, particularly conifers.

KEY WORDS: Heartwood, sapwood, weight, logs, growing tree.

## INTRODUCTION

In the xylem of growing trees water fills both free spaces in the cell walls (hygroscopic water) and capillary spaces (free water). It supports physiological processes and to a certain extent determines tree growth. For this reason its share in the tree mass is very high, sometimes even exceeding that of xylem. As a result transport of logs obtained from fresh-felled trees is mainly equivalent to the transport of contained water. One of the methods to reduce the mass of logs and the resulting transportation costs is natural (air) drying in the cutting area. Such a solution has been practiced mainly in the case of fuel wood (Acuna et al. 2012, Brand et al. 2011). However, in recent years we have been observing increased interest in problems related with optimisation of transport of industrial timber (Kłapeć et al. 2017). This is connected with a significant increase in timber harvesting. For example in Poland the volume of harvested timber increased from 31 945 thousand $m^3$ in 2005 to 40 901 thousand $m^3$ in 2016 (GUS 2017). As a consequence the number of shipments, fuel consumption and greenhouse emissions have grown. Competitiveness of timber in relation to other materials consists in the exceptionally advantageous ratio of energy required to produce it and energy needed to obtain, transport and process it. This competitive advantage is reduced if energy consumed for its harvesting, processing and particularly transport will be increasing.

The weight of the load is a factor affecting transportation costs. It depends first of all on the type of assortments, the share of bark and impurities, but to the greatest extent it depends on wood moisture content (Trzciński et al. 2018). Moisture content is a physical property, highly variable and diverse. In growing trees it is affected, among other things, by the season of the year, while in stored logs it depends on the time from felling, method and conditions of storage and the tree species (Garret 1985, Röser et al. 2011, Erber et al. 2012, Visser et al. 2014, Erber and Küchmaier 2017). For example, inter-species differences in moisture content result mainly from the presence or absence of heartwood. Heartwood is the part of the trunk, which does not participate in physiological processes and for this reason it typically has a much lower moisture content than sapwood. For instance in pine the sapwood moisture content is almost three-fold greater than that of heartwood. The share of heartwood in the trunk increases with age, thus the total (mean) moisture content in older pines will be lower in comparison to that in younger trees (Millers 2013).

Coniferous are a classical example changes of properties within-stem. A markedly lower density is found in the central part of the cross-section and the apical part of the trunk (Jelonek et al. 2009, Witkowska and Lachowicz 2013, Wąsik et al. 2015, Roszyk et al. 2016). This is caused e.g. by the presence of juvenile wood differing in its structure and properties from mature wood (Tomczak et al. 2009, Boruszewski et al. 2017). Different relationships are found in ring porous wood species, including oak. This group is characterised by relatively high density near the pith (Zhang et al. 1993, Bergès et al. 2000, Longuetaud et al. 2016, Sousa et al. 2016, Longuetaud et al. 2017).

Wood density is strongly correlated with moisture content. An increase in moisture content of dry wood results in its increased volume and mass. Upon exceeding the fibre saturation point only an increase in mass is observed. If dry wood has low density it means that it is highly porous and may absorb more water (Pratt et al. 2007). In many species density of dry wood at the base of the trunk is greater than in the apical section. This may explain the difference in green density of logs between these parts of the tree. Such an effect may be observed particularly in softwood, e.g. pine (Tomczak et al. 2016a), but it is also reported in hardwood species such as oak (Tomczak et al. 2015b) and birch (Tomczak and Jelonek 2015).

Due to the presence of water the weight and green density are always greater than those of stored timber. Highly dynamic losses of moisture content are observed in the very first days after felling, while later changes in moisture content are much smaller (Sinclair 1984, Garret 1985). Occasionally moisture content is even observed to periodically increase. This may be recorded at intensive rainfall and high humidity (Tomczak et al. 2016b). Nevertheless, under favourable conditions a considerable loss in moisture content and mass may be obtained within a short time already at the felling site (Tomczak et al. 2018). As it is indicated by studies concerning natural drying of fuelwood or industrial wood and its transport, it is both practically and economically justified to efficiently utilise the effects of this phenomenon (Busenius et al. 2015, Kanzian et al. 2016, Erber and Küchmaier 2017). Guidelines or models characterising natural drying of timber in the cutting area may be developed based on studies concerning wood moisture content in growing trees and studies determining measurable variables influencing variability of this trait in analysed tree populations. For this reason the primary aim of this study was to determine wood moisture content in growing trees in the selected season of the year, i.e. in the summer period when fuelwood is typically harvested and stored. Additionally wood density within-stem was determined. It is a trait affected by numerous external factors, the site, geographical location, etc., with which moisture content is strongly correlated. The analyses were conducted in a selected area, the trees were of a specific age and for this reason next to moisture content wood density also needed to be determined and characterised.

## MATERIAL AND METHODS

Material for analyses was collected on 4 July 2017. The investigations were performed in one oak stand located in the Murowana Goślina Experimental Forest Station (the Poznań University of Life Sciences) (geographical coordinates: N 52°32'40.797"; S 17°4'5.132"; 105 m a.s.l.) (Fig. 1). The age of the stand was 77 years, the plant community *Calamagrostio arundinaceae-Quercetum petraeae* (www.bdl.lasy.gov.pl; accessed 20.12.2017).

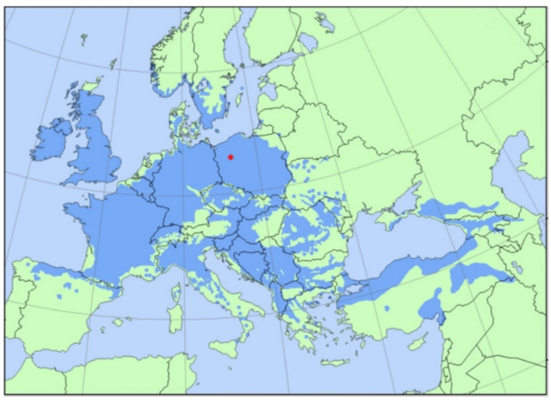

*Fig. 1: The natural range of sessile oak and the location of the research area (www.euforgen.org).*

From among trees selected for felling within a commercial thinning a total of 100 mean sample trees were chosen, representing various classes in terms of their diameters (min. 13 cm – max. 27 cm). The average diameter at breast height of a mean sample tree was 19 cm outside bark.

In the trunk of each mean sample tree an increment core was collected at a breast height ($d_{1.3}$) using an increment borer. Next it was divided into samples of 2 cm in length, each representing a different part of the cross stem section. The first sample was located 0.5 cm from the pith (*H1*), while the centre of the next (*H2*) coincided with the centre of the section indicating the heartwood. The third sample (*H3*) was collected at 0.5 cm from the boundary between heartwood and sapwood. The fourth sample was located in sapwood, minimum 0.5 cm from heartwood. In a situation, in which the length of the increment core prevented the identification of samples at very small tree diameters sample *H2* or samples *H2* and *H3* were not collected (Fig. 2).

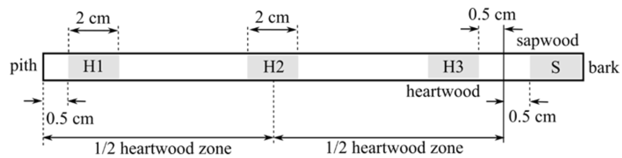


*Fig. 2: Sample preparation on trunk cross-section.*

Additionally, from 9 felled trees increment cores were collected along the stem – the first from the butt end and the successive ones at every 2.5 m. At each level the increment core was divided according to the adopted schema (Fig. 2).

After labelling samples were weighed using an electronic scale accurate to 0.01 g. After weighing the sample volume was determined by the method suggested by Pérez-Harguindeguy et al. (2016). A length of samples was measured using an electronic caliper accurate to 0.1 mm. Properties in green wood were measured on site immediately after the increment cores had been collected.

After samples were transported to the laboratory they were placed in electric muffle at 105°C. The drying was practiced in electric muffle until the constant mass of samples reached (EN ISO 18134-2: 2017).

Oven - dry density ($Q_s$) was calculated using Eq. 1, while that of green density ($Q_m$) - using Eq. 2. Absolute moisture content ($MC$) was determined using Eq. 3:

$$Q_s = \frac{m_s}{V_s} \qquad \left(\frac{g}{cm^3}\right) \tag{1}$$

$$Q_m = \frac{m_m}{V_m} \qquad \left(\frac{g}{cm^3}\right) \tag{2}$$

$$MC = \frac{m_w - m_s}{m_s} * 100 \qquad (\%) \tag{3}$$

where: $m_m$ – mass of green wood,
$m_s$ – mass of dry wood,
$V_m$ – volume of green wood,
$V_s$ – volume of dry wood.

In order to compare losses in moisture content the data were analysed statistically. In the first step the Lillefors test was performed in order to verify the normal distribution of data. The test assumes that a statistically significant result makes it possible to reject the hypothesis on the normal distribution of data. In such a situation the distribution of data between independent groups was compared using the non-parametric Kolmogorov–Smirnov test. The Kruskal–Wallis test was applied when comparing more than 2 groups of data. When the zero hypothesis was rejected, the post-hoc multiple comparisons of mean ranks were used for all samples. Statistical inference was performed at the significance level α=0.05. Calculations were made using the Statistica 13.1PL software package (StatSoft Inc.).

## RESULTS AND DISCUSSION

At the dbh the average green density was 0.984 g•cm$^{-3}$, while that of oven – dry density was 0.638 g•cm$^{-3}$. Absolute moisture content of tested wood was established at 62.4%.

Greater green density and oven-dry density were found in the central part of the trunk, near the pith. Oven-dry density differences was greater than differences of green density. Changes in moisture content had a completely different distribution than wood density. The moisture content was increasing in the direction from the pith to the bark by approx. 2% between each measurement point. Between samples located near the pith (*H1*) and those located at the sapwood (*S*) the difference in *MC* amounted to almost 9 percentage points (Tab. 1).

*Tab. 1: Green density, oven - dry density and moisture content changes on the cross-section of the trunk (dbh).*

| Properties | Part of the cross-section | Mean | SD | VC (%) | Min | Max | q25 | Median | q75 |
|---|---|---|---|---|---|---|---|---|---|
| $Q_m$ ($g \cdot cm^{-3}$) | H1 | 1.040 | 0.088 | 8.451 | 0.666 | 1.279 | 0.984 | 1.052 | 1.095 |
| | H2 | 1.036 | 0.056 | 5.366 | 0.880 | 1.125 | 1.006 | 1.046 | 1.065 |
| | H3 | 1.000 | 0.072 | 7.198 | 0.808 | 1.175 | 0.952 | 1.009 | 1.039 |
| | S | 0.902 | 0.127 | 14.049 | 0.617 | 1.278 | 0.826 | 0.899 | 0.976 |
| | All | 0.984 | 0.113 | 11.483 | 0.617 | 1.279 | 0.926 | 0.997 | 1.056 |
| $Q_s$ ($g \cdot cm^{-3}$) | H1 | 0.701 | 0.067 | 9.543 | 0.566 | 0.936 | 0.656 | 0.692 | 0.734 |
| | H2 | 0.676 | 0.045 | 6.643 | 0.595 | 0.764 | 0.646 | 0.686 | 0.709 |
| | H3 | 0.639 | 0.068 | 10.566 | 0.463 | 0.950 | 0.595 | 0.640 | 0.669 |
| | S | 0.463 | 0.105 | 22.752 | 0.340 | 0.880 | 0.495 | 0.558 | 0.628 |
| | All | 0.638 | 0.098 | 15.335 | 0.340 | 0.950 | 0.584 | 0.646 | 0.701 |
| *MC* (%) | H1 | 57.60 | 14.37 | 24.94 | 27.86 | 100.00 | 51.67 | 57.88 | 66.03 |
| | H2 | 59.04 | 10.04 | 17.00 | 35.48 | 82.61 | 53.57 | 58.62 | 66.67 |
| | H3 | 64.34 | 14.39 | 22.37 | 28.21 | 131.25 | 55.56 | 65.38 | 70.83 |
| | S | 66.32 | 20.49 | 30.90 | 28.08 | 120.00 | 52.27 | 66.67 | 80.00 |
| | All | 62.36 | 16.72 | 26.81 | 27.86 | 131.25 | 53.71 | 61.72 | 71.13 |

Number of samples, n: H1=100, H2=25, H3=83, S=100, all=308

Legend: $Q_m$ – green density, $Q_s$ – oven - dry density, *MC* – moisture content, *dbh* – diameter at breast height, *H1, H2, H3* – heartwood samples, *S* – sapwood samples

Statistically significant differences in the green density were observed between samples *H1*, located closest to the pith, in the heartwood, and *S*, i.e. in the sapwood. Oven – dry density *H3* samples was a significantly lower value in comparison to *H1* samples. In turn, moisture content of wood differed significantly between *H1* and *H3*, *H2* and *H3*, *H1* and *S*, *H2* and *S*. No significant differences were recorded between moisture contents in the heartwood part adjacent to sapwood (*H3*) and that of sapwood (*S*) (Tab. 2).

*Tab. 2: Results of Kruskal-Wallis test.*

| | | H1 | H2 | H3 | S |
|---|---|---|---|---|---|
| *Qm* | H1 | * | * | * | 0.000000 |
| | H2 | * | * | * | 0.000000 |
| | H3 | 0.033873 | * | * | 0.000000 |
| *Qs* | H1 | * | * | * | 0.000000 |
| | H2 | * | * | * | 0.000001 |
| | H3 | 0.000001 | * | * | 0.000142 |

| | | | | | |
|---|---|---|---|---|---|
| *MC* | H1 | * | * | * | 0.000416 |
| | H2 | * | * | * | 0.036893 |
| | H3 | 0.001448 | 0.034609 | * | * |

*differences not-significant, other significant with p<0.05

For heartwood samples mean green density was higher by approx. 1 g•cm$^{-3}$ than sapwood density (Fig. 3a). It is similar to oven – dry density (Fig. 3b). Average moisture content in heartwood was 60.57% and it was lower by approx. 6% from moisture content in sapwood (Fig. 3c).

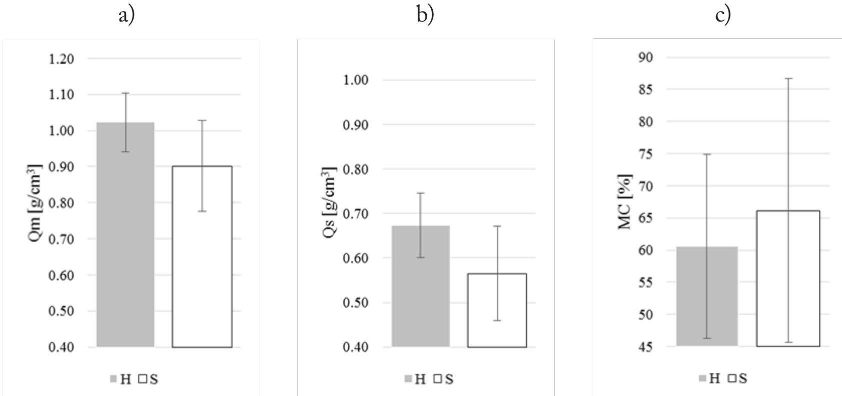


*Fig. 3 a-c: Comparison of selected properties of heartwood and sapwood on trunk cross-section ($d_{1.3}$) (n = 100): a – green density, b – oven-dry density, c – moisture content.*

Along the trunk green density near the pith (*H1*) was decreasing. In contrast, it was slightly increasing in the sapwood (*S*) in the direction from the base to the stem apex. General heartwood green density near the pith and sapwood green density along of the trunk was very similar (Fig. 4). In relation to the density of dry wood it was found that its value was very similar in near the pith (*H1*). The sapwood (*S*) oven – dry density was slightly higher in the bottom of the trunk. The tree trunks did not have a large diameter, hence no significant differences in density on cross-section (Fig. 5). Between the base of the trunk and the apex difference in moisture contents was approx. 10 – 20 percentage points. In the case of the differences in moisture contents between *H1* and *S* they are not high in the lower part of the trunk. With an increase in the distance from the base of the trunk they slightly increased (Fig. 6).

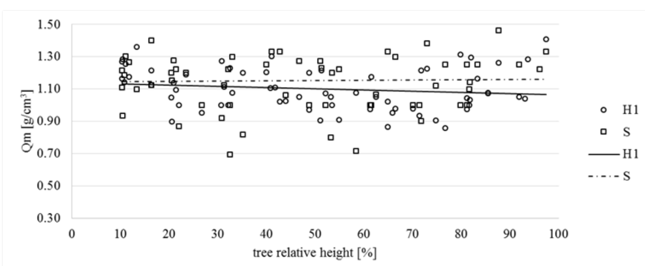


*Fig. 4: Changes in the green density along the trunk for heartwood (H1) and sapwood (S) samples.*

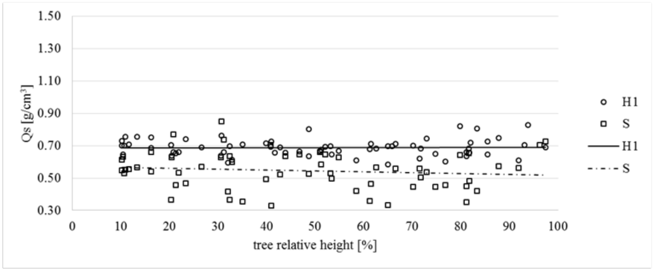


*Fig. 5: Changes in the oven-dry density along the trunk for heartwood (H1) and sapwood (S) samples.*

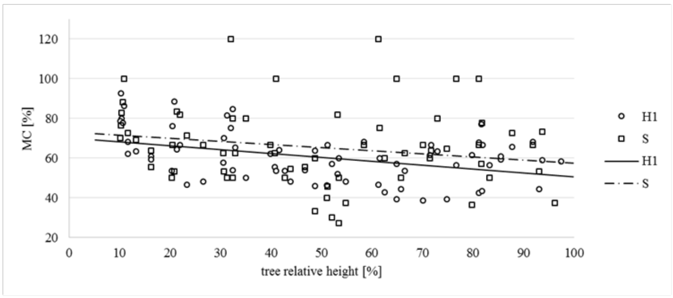


*Fig. 6: Changes in moisture content along the trunk for heartwood (H1) and sapwood (S) samples.*

Among other things the aim of this study was to determine moisture content and green density of oak wood. Wood density is affected by the geographical location, particularly markedly in species with large ranges of distribution, as well as many other factors, including e.g. the age of trees. For this reason it needs to be stressed that the experimental site, in which the study was conducted, is located in the Forest Experimental Station in Murowana Goślina near Poznań (Poland). It is the north-eastern area of the range of distribution for sessile oak in Europe (Fig. 1).

Mean green density was 0.984 g•cm$^{-3}$, while oven-dry density was 0.638 g•cm$^{-3}$, and it is comparable to that in other oak species (Vavrčík and Gryc 2012, Pásztory et al. 2014 Zeidler and Borůvka 2016). The analyses were conducted in the summer period (July) in a 77-year old stand, in which the average diameter at breast height of the mean sample trees was 19 cm outside bark. Since the analysed properties are affected by cambial age, the results may be comparable to those of trees of similar age. In ring porous wood species changes in density at the cross stem section are characteristic, similarly as it is the case with coniferous species, except that in coniferous species density grows in the direction from the pith to the bark (Jelonek et al. 2009, Tomczak et al. 2011, Zeidler et al. 2014), while e.g. in oak it decreases (Guilley et al. 1999, Bergès et al. 2000, Longuetaud et al. 2016, Longuetaud et al. 2017). This trait is already observed in relatively young trees, which was shown based on these results. This analysis was conducted using four measurement points distributed along the ray. Three of them were located within the heartwood and one - in the sapwood. A greater green density and oven – dry density were found in heartwood, mainly near the pith. Differences between samples from heartwood and sapwood were statistically significant, although the distances between them (on the cross section of the trunk) were not large (small trunk diameters). In oak changes in oven-dry density at the cross stem section are significant (Pásztory et al. 2014). At a low density xylem may accumulate more water than wood of high density (Pratt et al. 2007). In our study moisture content in sapwood was higher than moisture content in heartwood. First of all, it's the effect of physiological activity of the sapwood. On the other hand, it can also be related to the density of wood.

Oak is a tree, in which the heartwood occupies an exceptionally large part of the stem cross-section. Typically sapwood is very narrow, with a width of maximum several centimeters. Heartwood in oaks is also exceptional in another respect, as it has a very high moisture content, comparable to that of sapwood and unlike to other heartwood species.

High moisture content in the oak heartwood affects the weight of timber obtained from freshly-felled trees. Tomczak et al. (2015b) reported that 1 $m^3$ of oak logs weighs from 936 to approx. 1020 kg. For comparison, the mass of 1 $m^3$ birch logs is 878 kg (Tomczak and Jelonek 2015, Tomczak et al. 2015a), while that of beech logs is 942 kg. In oak green density of logs is high as it is the case in non-heartwood species, which have no marked density or moisture gradients at the cross stem section. It is an exceptional situation in comparison to heartwood species, particularly conifers. Heartwood is the physiologically inactive part of the trunk, which does not participate in the conduction process. For this reason in most such species it has a mark endly lower moisture content than sapwood. Analyses were conducted in the summer period (July). In that period wood moisture content is lower than in winter (Cinotti 1989). Analyses presented by Cinotti (1989) also showed that seasonal changes affect the entire cross stem section. Moisture content in the central part of the cross-section changes similarly as moisture content in sapwood.

Water stored in wood accounts for a considerable share of its weight. At a greater weight of the transported load fuel consumption and GHG emissions increase, which means that environmental costs increase as well (Busenius et al. 2015, Kanzian et al. 2016).

A significant loss of weight as a result of natural processes may be obtained within a relatively short time of around a fortnight (Tomczak et al. 2016b, 2018). However, this conclusion was drawn from studies conducted only in the summer period. Under adverse conditions, typically autumn or winter, moisture content (mass) of stored timber decreases very slowly, while occasionally at intensive precipitation and high humidity we may observe an opposite phenomenon, i.e. its increase (Routa et al. 2015a, b). For this reason changes in performance parameters of timber are modelled based on weather data measured with high frequency (Erber et al. 2016, 2017).

To obtain more general, although potentially less accurate formulas, which would nevertheless prove to be more universal, a database of averaged data is required, including information on moisture contents in wood of growing trees. Collection of data for a database of adequate size is rather difficult due to the large number of variables, including e.g. age, site and social class of tree position. In the case of the trunk it is mainly connected with variation at the cross section and along the trunk. The experiment was conducted on only one stand, as it aims at determining the moisture gradient for wood at various trunk parts, with no effect of other variables, in a specific season of the year. Probably in an older or younger stand, in a more fertile site or in one less abundant in nutrients the results would be comparable. This trait may be assumed to be species-specific. However, this hypothesis needs to be confirmed in further studies, covering not only trees of various ages in various stands, but also in various seasons, at least in the summer and winter.

## CONCLUSIONS

The primary aim of this study was to determine wood moisture content in growing trees in the selected season of the year. Absolute moisture content of tested wood was established at 62.4%. Average moisture content in heartwood was 60.6% and it was lower by approx. 6% from moisture content in sapwood. Moisture content of the oak heartwood is high, similar to central part of the trunk of non – heartwood species. It is an exceptional situation in comparison to heartwood species, particularly conifers. High moisture content in the oak heartwood affects the high weight of timber obtained from freshly-felled trees. The experiment also confirmed that wood density from the central part of the cross stem section (*H1*) and at the sapwood (*S*) were similar along the trunk, while moisture content were gradually decreased. Between the base of the trunk and the apex difference in moisture contents was approx. 10 – 20 percentage points. In this case, it may have an impact on the time of natural drying logs obtained from a different part of the trunks.

## ACKNOWLEDGMENT

This research was funded by the Polish Ministry of Science and Higher Education through subsidies for the Faculty of Forestry Poznań University of Life Sciences.

The authors would like to thank the staff of the Forest Experimental Station in Murowana Goślina for their help with the experiment and to an anonymous reviewer for commenting and improving scientific quality of this paper.

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